

## Miscellaneous

### Papers and presentations of Fischer-Tropsch diesel fuel studies

1. Lyons, James M., "The Effect of Diesel Fuel Properties on Emissions From Current and Future-Technology Engines," Sierra Research, Inc., California.

*This paper looks at the diesel fuel properties and the affects on emissions. The conclusion is the lower the sulfur and aromatics, the better the emissions profile and the higher the cetane the lower the nitrogen oxide emissions.*

2. Belcher, Jack, "Tests Begin to Qualify Syntroleum Fuel for U.S. Fleet Mandates," Gas-to-Liquids News, Vol. II, No. 3, March 1999.

*Article shows the continued tests on Fischer-Tropsch diesel and how it reduces emissions compared to conventional diesel and CARB diesel.*

3. Belcher, Jack, "Shell GTL Hopes for April, 2000 Restart; 25% Capacity Boost," Gas-to-Liquids News, Vol. II, No. 3, March 1999.

*Article discussing the Shell GTL facility and improvements in efficiency and lower capital potential. Shell expects a restart in early 2000.*

4. Peckham, Jack, "Joint European Study Finds Benefits of FT Diesel," Gas-to-Liquids News, January 1999.

*The article reviews a joint European study sponsored by the European Commission to look at emissions from Fischer-Tropsch diesel, biodiesel and ultra-low sulfur diesels. Fischer-Tropsch diesel was the best from all aspects of handling and emissions as well as a blending stock for improving other diesel fuels.*

5. Peckham, Jack, "Study Confirms FT Diesel Cuts Emissions in Real Vehicles," Gas-to-Liquids News, January 1999.

*Article reviews the SAE study on unmodified Detroit diesel buses and showed a significant reduction in emissions in real vehicles in real operations. The study was completed by the Department of Energy, The National Renewable Energy Laboratory and West Virginia University.*

6. Peckham, Jack, "Fischer-Tropsch Diesel Cuts All Emissions, Unlike Biodiesel," Gas-to-Liquids News, May 1999.

*Article reviews the study by West Virginia University on tests comparing biodiesel and Fischer-Tropsch diesel and all tests indicate that Fischer-Tropsch diesel reduces emissions and is a better blending stock than biodiesel.*

7. Gray, David, and Glen Tomlinson, "Natural Gas to Ultra-Clean Liquid Transportation Fuels," Mitretek Systems, Clean Fuels Strategy Conference, London, 1998.

*Presentation on the technical and economic risks of GTL applications showing there is significant potential in GTL.*

8. Slodowske, Warren J., "Diesel Technology Today & A Bit Beyond," Navistar, Diesel Issues Forum, 1999.

*Presentation on the significant progress by diesel engine manufacturers on the reduction of emissions over the past ten years. The barriers to further improvements are the fuel quality and oil quality. The one comment of Fischer-Tropsch diesel is that it is the "ultimate" fuel for diesel engines.*

9. Grimes, Gary, "Economics and Experience of Blending Fischer-Tropsch Diesel at Paramount Petroleum," Paramount Petroleum, Gas-To-Liquids Processing 99 Conference, Texas, 1999.

*Paramount Refinery has several years of experience using Fischer-Tropsch diesel as a blending stock to meet the CARB diesel requirements in California. This presentation describes that experience and the Tosco Refinery's similar experience and the benefits of Fischer-Tropsch diesel as a blending stock.*

10. Vachon, Tom, "Clean Diesels, Clean Fuels," Caterpillar, Inc., EFI Conference, 1999.

*The presentation makes an argument for cleaner fuels and the need to drive the diesel standards toward that of Fischer-Tropsch diesel with ultra-low sulfur and aromatics.*

11. Tower III, Arthur W., "Fischer-Tropsch Technology – Gas-to-Liquids, Solids-to-liquids, Liquids-to-Liquids", Howard, Weil, Labouisse, Freidrichs Incorporated, 1998.

*General paper on all F-T technologies, the stage of development, the market, and opportunities.*

## **The Effect of Diesel Fuel Properties on Emissions From Current and Future-Technology Engines**

Prepared for the API Diesel Fuel Subcommittee by:

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*Former Comb*

### **Study Objectives**

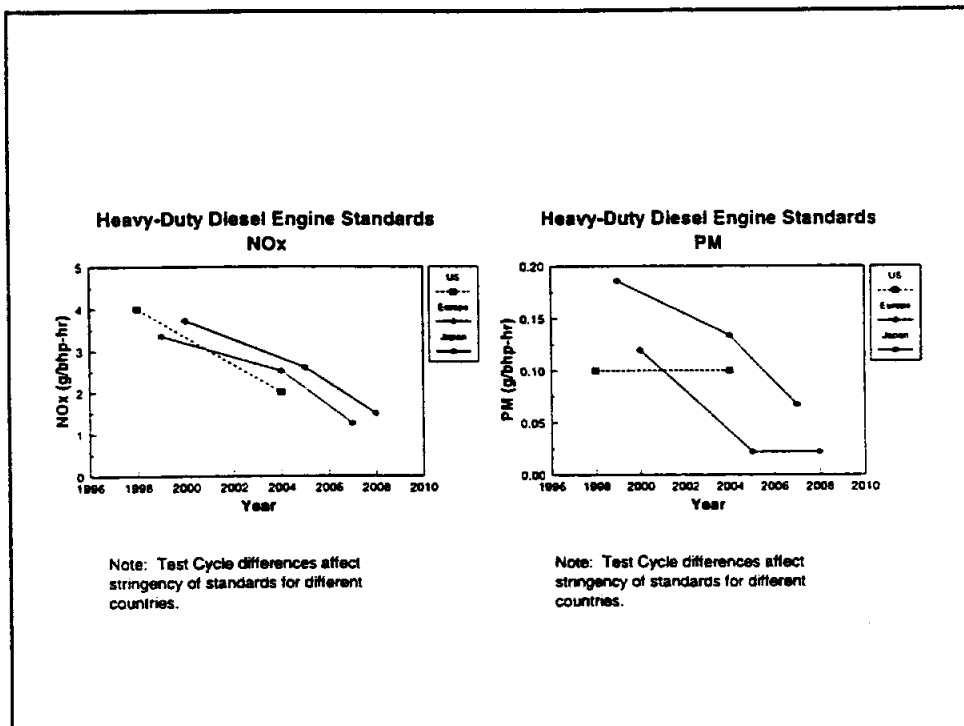
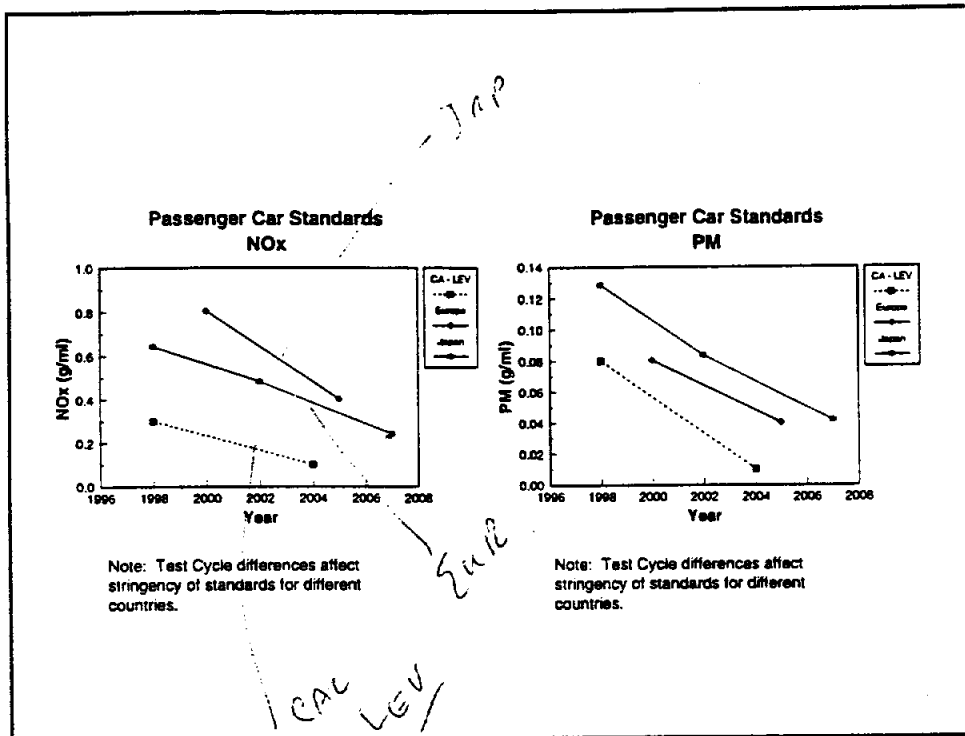
- Summarize what is known regarding the impact of Diesel fuel composition on Diesel engines currently used in light- and heavy-duty applications;
- Identify and review the available information regarding technologies that will be employed on future Diesel engines and in particular, the implications of those technologies with respect to Diesel fuel composition;
- Review the available information regarding the impact of Diesel fuel composition on emissions from future Diesel engines; and
- Identify areas where additional research is needed to understand the effect of Diesel fuel composition on the emissions performance of future Diesel engines.

## Outline

- Emission Requirements for Future Engines
- Fuel Requirements for Future Engines - Current Thinking
- Impact of Fuel Composition on Emissions from Current Diesel Engines
- Future Diesel Engines - Engine Modifications
- Future Diesel Engines - Aftertreatment Devices
- Emission Reduction Potential & Fuel Requirements
- Summary and Recommendations

## Emission Requirements for Future Engines

NO<sub>x</sub>    ↓↓  
PM       ↓↓  
HC   = or ↓  
CO   = or ↓  
Fuel Economy   = or ↑



## Fuel Requirements for Future Engines - Current Thinking

Density	↓
T90/T95	↓
Aromatics	↓
Polycyclics	↓
Sulfur	↓
Cetane	↑

"World-Wide" Diesel Fuel Specifications Recommended by Engine and Vehicle Manufacturers			
Diesel Fuel Property	Emissions Control Requirements		
	Minimal	Stringent	Advanced
Density (g/cm <sup>3</sup> ) □	0.820-0.860	0.820-0.850	0.820-0.840
T95 (°F - max) □	698	671	644
FBP (°F - max) □	-	689	662
Aromatics (vol % - max) □	-	25	15
Polycyclic Aromatics (vol% - max) □	-	5	2
Sulfur (ppm - max) □	5,000	300	30
Cetane Number (min) □	48	53	55
Cetane Index (min) □	45	50	52

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**Impact of Fuel Composition Changes on Emissions  
of Current Diesel Engines**

Change	Heavy-Duty				Light-Duty			
	NOx		PM		NOx		PM	
	High <sup>a</sup>	Low <sup>b</sup>	High	Low	1D1	D1	1D1	D1
↓ Sulfur (below 0.05%)	None	None	↓	↓	None	None	↓	↓
↑ Cetane	↓	↓	None	None	↑	↓	None	↑
↓ Density	↓	↓	↓↓	None	None	↑	↓↓	↓↓
↓ T90/T95	↓	↓	None	None	↑	↑	None	↓
↓ Aromatics	↓	↓	None	None	↓	↓	↓	↓
↓ Polycyclics	↓	↓	↓↓	None	↓	↓	↓	↓

<sup>a</sup> Engines with high emission levels.

<sup>b</sup> Engines with low emission levels.

*From  
European  
Study  
Main Catalysts*

### **Future Diesel Engines - Engine Modifications**

- Engine Design
  - Air motion/swirl
  - 4 Valves Per Cylinder
  - Reduced Oil Consumption
- Turbocharging
  - Variable Geometry
  - Multiple Stage
- EGR
  - EGR & Water Injection

### **Future Diesel Engines - Engine Modifications (continued)**

- Fuel Injection
  - Pilot Injection/Rate Shaping/Multiple Injections
  - Higher Pressures
  - Smaller Orifices
  - Variable Orifices
  - Homogenous Charge
- Electronic Engine Control Systems
  - Variable Valve Timing
  - EGR
  - Turbochargers
  - Fuel Injection
  - OBD
  - NOx Sensors



### **Future Diesel Engines - Aftertreatment**

- Lean NOx Catalysts
  - Passive Systems
  - Active Systems
  - Precious and Base Metal Catalysts
- SCR Systems
- NOx Absorbers
- Non-Thermal Plasma Systems
  - Stand alone
  - Pretreatment devices for NOx Aftertreatment/Particulate Traps
- Oxidation Catalysts
- Particulate Traps
  - Fuel based catalysts

### **Emission Reduction Potential of Engine Modifications**

- Difficult to assess emission reduction potential of individual engine modifications.
- EGR alone on heavy-duty engines can provide 30-40% reduction in NOx emissions with increase in PM emissions.
- Lower limit on engine-out heavy-duty engine NOx at current PM levels without aftertreatment is on the order of 1.5 g/bhp-hr.
- Engine modifications will probably allow compliance with most near term emission standards but not with longer term European standards, which will likely require aftertreatment.
- Homogenous charge compression ignition engines may allow compliance with longer term NOx and PM levels without aftertreatment.

## Fuel Requirements Associated with Engine Modifications

- Engines using EGR may experience durability problems at current fuel sulfur levels (e.g. 500 ppmw max).
- Testing of proto-type heavy-duty engines designed to meet U.S. 2004 standards shows small (~10%) NO<sub>x</sub> impacts associated with reductions in density and aromatic and polycyclic aromatic levels in combination with increasing cetane.
- Available data continues to indicate that PM and NO<sub>x</sub> engine-out emissions from advanced heavy-duty engines are not particularly sensitive to fuel properties, even when "clean" Diesel fuels such as Fisher-Tropsch fuels are used.
- Overall data are limited, particularly for light- and medium-duty engines.

Emission Reduction Potential and Fuel Requirements - Aftertreatment Devices			
Devices	Potential NO <sub>x</sub> Reduction	Potential PM Reduction	Fuel Requirements
Passive Lean NO <sub>x</sub>	5-10%	0-20%	Ultra Low Sulfur? HC Composition?
Active Lean NO <sub>x</sub>	20-30%	0-20%	Ultra Low Sulfur? HC Composition?
Selective Catalytic Reduction	50-85%	-	Ultra Low Sulfur?
NO <sub>x</sub> Absorbers	?	-	Ultra Low Sulfur
Plasma Devices	?	?	?
Oxidation Catalysts	-	10-30%	Ultra Low Sulfur?
Particulate Traps - Fuel Additives	-	70-90%	None
Particulate Traps - Ox Cat/NO <sub>2</sub>	-	70-90%	Ultra Low Sulfur

### **Fuel Requirements for Future Engines - Based on Available Data**

Density	?
T90/T95	?
Aromatics	?
• Polycyclics	?
Sulfur	↓
Cetane	?

### **Summary and Recommendations**

1. Except for sulfur content, available data do not indicate a significant impact of Diesel fuel composition on engine-out emissions and aftertreatment device performance for engines/vehicles capable of meeting future NOx and PM standards.
2. Data regarding sulfur effects indicate that reducing fuel sulfur below the nominal 500 ppmw level will reduce sulfate emissions, improve durability of EGR-equipped engines, and enable certain types of aftertreatment devices. In addition, there are on going studies of sulfur impacts on engines equipped with advanced aftertreatment devices.

### **Summary and Recommendations (continued)**

3. Available data indicate that PM and NOx emissions from engines meeting current standards are relatively insensitive to changes in density, aromatic content, T90/T95 temperatures, and cetane number/index.
4. Comprehensive testing of fuel property impacts on proto-type future engines/vehicles is needed to justify additional changes to Diesel fuel properties with the possible exception of sulfur content.

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March 1999, Vol. II, No.3

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the U.S. (see GTLN, Nov. 98, p1)

Under EPACT, a substantial percentage of new vehicle purchases for certain fleets must be "capable of running on alternative fuels." The mandate affects fleets with a minimum size of 50 vehicles, including federal and state fleets, and "fuel provider" fleets, which includes gas and electric utilities. That percentage is ratcheted up each year, reaching 75% of federal

(Continued, p2)

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Air Separation Unit (ASU) from France's Air Liquide (the original maker of the unit destroyed in the blast) in early 2000. Following that, Shell expects plant start-up is April, 2000, explains A. Suhaili Idrus, General Manager-Marketing, Shell Middle Distillate Synthesis (SMDS).

Idrus and Bram Pegels, SMDS

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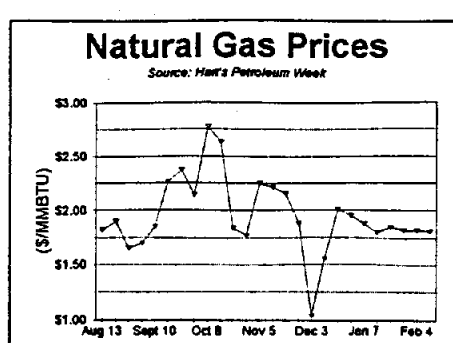
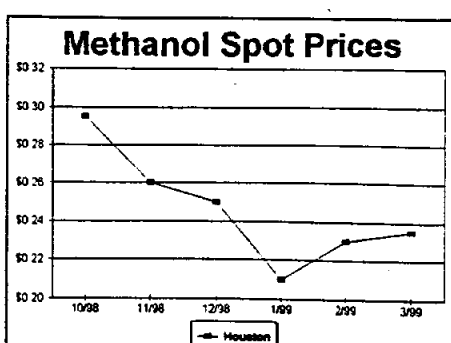
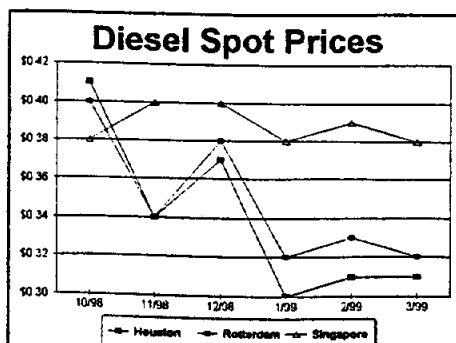
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## GTLN Market Snapshot



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## Epact ... (from p1)

fleet purchases in 2000, 90% of fuel provider purchases in 2000, and 75% of state fleet purchases in 2001. Despite the fact that these purchases are required by law, the alternative fuel market is not achieving its full potential because a very large percentage of those vehicles have dual fuel capabilities and are being run on conventional gasoline.

Should fleet managers actually use alternative fuels, the potential market for "alternative fuels" under EPACT could be as large as 600,000 b/d by 2010. Syntroleum would like for FT diesel fuel to qualify for a percentage of that market.

"Right now Syntroleum is producing suitable quantities of product to be tested," says Peter Snyder, vice president of product marketing, Syntroleum. Two types of tests will be performed at SWRI, he said. Chassis dynamometer and static tests will take place on vehicles using the fuel to measure exhaust output. Lubricity tests are being performed at the facility with the Lubrizol providing fuel additives for the tests.

The fuels will be compared to conventional #2 diesel as well as diesel that meets the more stringent California Air Resources Board (CARB) standards. In testing performed at the University of West Virginia, FT fuels provided by the Shell Bintulu facility showed 12% reductions for NOx, 18% for CO, 24% for PM and 40% for overall hydrocarbon emissions, when compared to conventional diesel (see GTLN, Jan. 99, p9).

Once the testing is completed,

assuming that the fuel meets EPA specs, "the next step will be to petition the Energy Secretary to consider allowing FT fuel to qualify as a city diesel under the Energy Policy Act," says Snyder. DOE could take as long as a year to make its determination. The SwRI data would be sent to DOE's Argonne Laboratory to verify the testing results.

## Diesel Loophole

When Congress set up the guidelines for EPACT, it defined alternative fuels to include methanol, ethanol, other alcohols, natural gas, liquefied petroleum gas, hydrogen, coal-derived liquid fuels; fuels derived from biological materials, electricity, "and any other fuel the Secretary determines, by rule, is substantially not petroleum and

Table 2: Exhaust emissions from hot-start FTP engine tests in g/bhp-hr.

Conventional No. 2 Diesel					
Test #	HC	CO	NO <sub>x</sub>	PM	CO <sub>2</sub>
6199803	0.316	1.573	5.475	0.119	647.52
6199804	0.352	1.578	5.367	0.121	641.86
6199805	0.370	1.602	5.277	0.121	641.85
Average	0.346	1.584	5.373	0.120	643.75
California No. 2 Diesel					
Test #	HC	CO	NO <sub>x</sub>	PM	CO <sub>2</sub>
61998012	0.299	1.111	4.915	0.102	618.57
61998013	0.293	1.136	5.049	0.108	615.06
61998014	0.229	1.025	4.716	0.119	613.82
Average	0.274	1.091	4.893	0.109	615.85
Fischer-Tropsch Diesel					
Test #	HC	CO	NO <sub>x</sub>	PM	CO <sub>2</sub>
6199807	0.211	0.991	4.722	0.108	610.88
6199808	0.209	0.954	4.853	0.102	612.97
6199809	0.174	0.959	4.445	0.101	610.62
Average	0.198	0.968	4.607	0.104	611.49

would yield substantial energy security benefits and substantial environmental benefits."

Biodiesel or B-20, because it is a blend of 20% bio-fuel and 80% conventional diesel, did not initially meet the definition as an alternative fuel, though it claims environmental benefits. Its proponents petitioned the DOE Secretary to designate it as such, but

(Continued, p11)

## Shell Proposes \$8.5 Billion Nigerian Natural Gas Plan

Royal Dutch/Shell has submitted a proposal for the largest industrial ever made in sub-Saharan Africa, a \$8.5 billion plan to upgrade Nigeria's oil and natural gas industries. Shell is in negotiations with government officials, other energy companies and contractors over the five-year plan, which would increase Nigerian oil output by one-third and would make Nigeria one of the leading producers of LNG.

The plan includes significant new development of Nigeria's offshore reserves, with over 600,000 b/d of new oil production. Shell also seeks to increase LNG production by launching

a new train at the Bonny Island plant, owned by Nigeria Liquefied Natural Gas. That group consists of Nigerian government officials, Shell, Elf Aquitaine, and Agip. That train is part of Shell's plan to develop four large offshore fields as well as an offshore gathering network.

Shell officials report the plan would bring in roughly \$20 billion to the state of Nigeria over 20 years. Shell would contribute about 70% of the capital for the plan, with the rest coming from the government of Nigeria and other participating oil companies.

Nigeria is currently involved in a major effort to make better use of its natural gas resources and end gas flaring by 2008. Currently the country flares about 75% of its gas production and reinjects an additional 12%. It is the world leader in flared gas (see *GTLN*, December 1998, p13).

The Nigerian government has enacted a number of tax incentives designed to attract international investment in its natural gas sector and has allotted \$450 million for gas-related investments, with a additional million going to other petroleum projects.

--Jack Belcher

## Epact ... (from p3)

when that process dragged on, Congress included some language in the 1999 Agricultural Appropriations Bill that directed DOE to designate the fuel under EPACT. That designation allows fleet managers to receive credits to meet the alternative fuel provisions without having to purchase expensive alternative fuels vehicles. However, B-20 approximately doubles the cost of diesel fuel.

Biodiesel's designation presents an interesting precedent for FT fuels, notes Snyder. "It opens up all kinds of possibilities." FT fuels could demon-

strate a number of advantages, he noted. There is no limit to how much can be produced, it can use the existing diesel fuel infrastructure, and it requires no engine or automobile modification. And like biodiesel, FT diesel could be blended with conventional diesel at various ratios.

### Gaining Support

FT diesels have an uphill battle in gaining acceptance from policy makers who have little or no knowledge of its environmental benefits. Syntroleum is not in any direct effort to communicate and lobby Congress on the fuel's

behalf and is currently concentrating on its research--attempting to present DOE with solid evidence about the fuel's benefits. Coalition building is difficult because large oil companies that are involved in FT fuels research have greater immediate concerns to manage with policy makers.

But as the fuel becomes better known, "we are getting support from some members of the natural gas lobby," Snyder says. That support could grow should the SWRI testing program report some positive results.

--Jack Belcher

## Kansas ... (from p4)

blending and demonstration to get the right fuel properties," said Suppes. "Once you identify a fuel that will work, then you need to find one that works better, that is more efficient. Modifications will continue," he says.

As for the cost, Suppes believes that, based on numerous industry studies, FT syncrude feedstocks from a large plant can be as

cheap as 50c/gal--when produced by natural gas--or as expensive as 78c/gal--when produced from coal. Other factors include the cost of blending components such as ethanol or diethyl ether.

Suppes believes that his FT diesel has tremendous potential in meeting environmental current and future statutes. "Syntroleum is testing an FT diesel and is looking at EPACT certification," he said, noting that his

fuel could have even greater emissions benefits. "You can put this fuel in old engines and still clean up cities."

On the whole, Suppes believes that he is developing the fuel with the best benefits in terms of emissions, lubricity and efficiency. "Preliminary engine tests indicate that these formulations are probably the best liquid fuel that has ever been recorded for use in a diesel engine."

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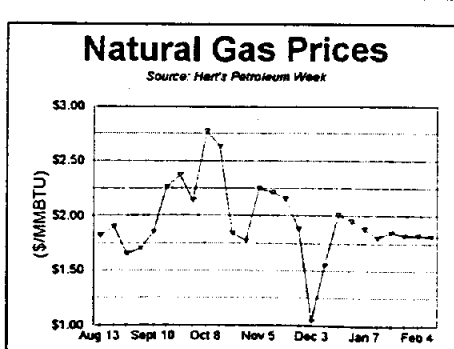
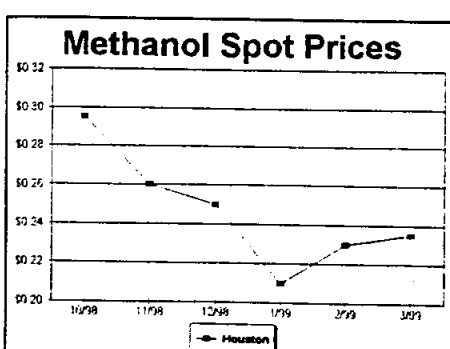
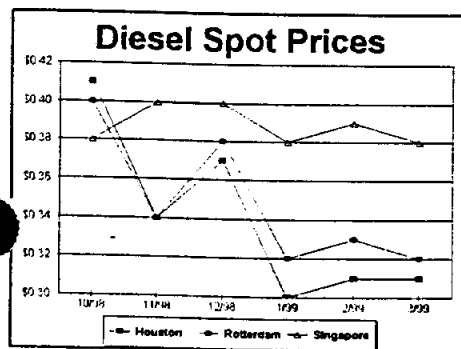
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## GTLN Market Snapshot





## Exclusive On-Site Report:

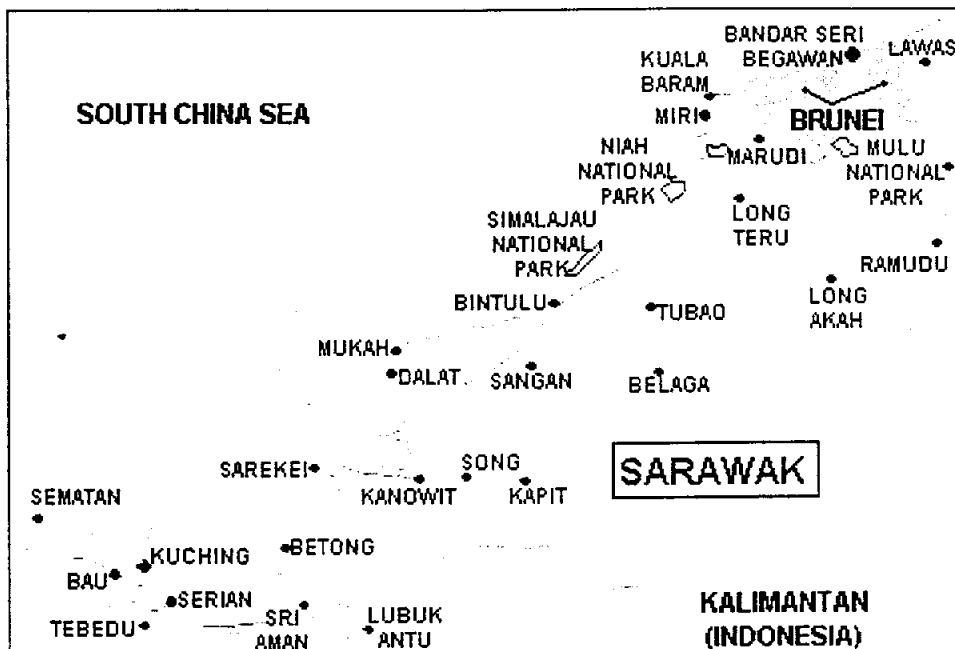
# Shell Bintulu Rising from the Ashes... (from p1)

General Manager-Manufacturing, gave *Gas To Liquids News* an exclusive tour of the SMDS plant in February, along with an overview of recent history and GTL products and technologies.

### New Technology in Rebuilt Plant

Second-generation catalysts and an innovative exhaust gas turbine are two of the new technology developments either planned or underway here.

The turbine would burn some of the low-Btu off-gas from the Heavy Paraffins Synthesis (HPS) process units, supplemented by gas from off-shore natural gas fields that feed the



SMDS plant.

Meantime, progress on the advanced catalyst front is moving quickly.

"In April 2000, our second-generation Heavy Paraffins Synthesis (HPS) catalyst is scheduled to come on-line" at SMDS, Idrus explains. This new catalyst has been pilot-scale tested at Shell research facilities in Amsterdam. Results so far are encouraging and this technology should produce more Fischer-Tropsch (FT) wax than the first-generation catalyst. Shell wants more output of FT

wax because Shell can realize a premium on this wax compared to middle distillates, he said.

### Understanding ASU Sensitivity

"The cryogenic industry is very aware of what happened at Bintulu," said SMDS General Manager-Manufacturing Bramr Pegels, who's been at the plant since its inception in 1992.

Evaluations by Shell scientists as well as experts from Air Products, Air Liquide and Linde ultimately led to a new ASU design with enhanced safety features. The new unit will have an advanced air treatment section to remove water, CO<sub>2</sub>, hydrocarbons, and other particulates.

In addition, the new system will include "much more air quality monitoring, PM counters and indicators showing whether the filters are working," Pegels said.

### Markets for FT Products

Some of the key markets for FT

(Continued, p8)

## Exclusive On-Site Report:

### Shell Bintulu Rising From The Ashes... (from p6)

waxes are in countries where candles play a major role in religious rites. For example: Mexico, an overwhelmingly Roman Catholic country, consumes 130,000 tons/year of candle wax.

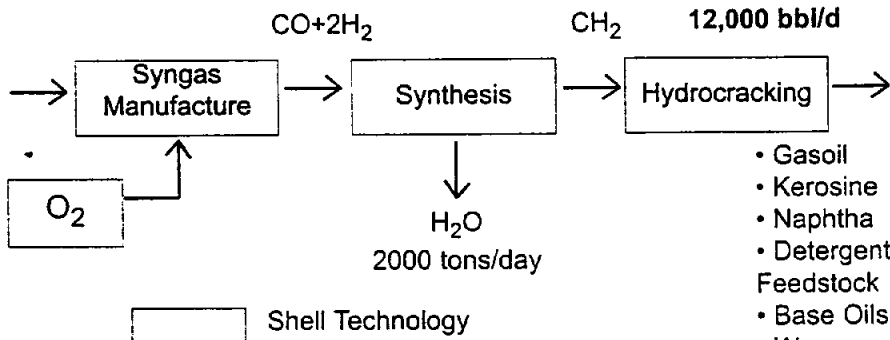
The world wax market has been depressed recently, however, by a surge of Far Eastern exports. In a 3 million tons/year world wax market, China produces about 1 million tons, 300,000 t/year going to the export market. Some of the main markets for Shell's FT products include:

\* Petrochemical feed naphtha. The C4 to C10 alkanes/ aliphatic hydrocarbons make ideal refinery cracker feedstocks for ethylene and other petrochemicals. The C12 to C22 alkanes

#### SMDS Malaysia Process

Natural Gas  
100 MMScf/d

Oil Products  
Chemical  
Feedstock  
12,000 bbl/d



Source: Shell Global Solutions

### Vital Statistics... (from p7)

#### Changes When Bintulu Returns to Production:

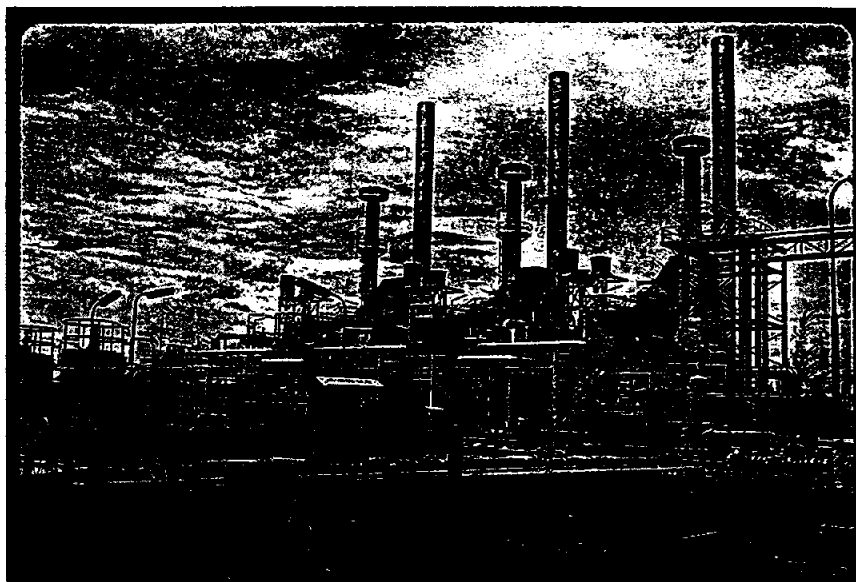
Shell will significantly increase reactor capacity in its Shell Gasification Process (SGP) unit. Each SGP unit processes 20 mmscf/d of gas converting over 95% of the methane into CO. When operating, burner life time exceeded two years and metal dusting was successfully controlled, Shell MDS expert Ad Punt explained at a recent GTL conference. The Heavy Paraffins Synthesis Process (HPS) will employ a new synthesis catalyst and larger reactors, enabling an output of 9,000 b/d per multitubular reactor. A modular design will allow for phased construction and phased inspection/shutdown maintenance, Punt said.

#### View of Future Shell GTL Plants:

While Shell hasn't publicly detailed plans for future GTL plants, it is believed to have postponed any projects as long as world oil prices continue to suffer today's low levels. Were it not for the substantial insurance settlement for the Bintulu explosion, Shell would not have proceeded with reconstruction of SMDS, under the current low oil-price scenario. It is also believed that Shell would not build its next SMDS plant with exactly the same emphasis Bintulu has on linear paraffins. Rather, it is possible that the next SMDS plant could focus more on higher olefins (C5-C20) for petrochemical customers. Potential SMDS plants could rise in Nigeria, the Middle East, Southeast Asia, or even Europe.

For a future GTL conversion project targeting transportation fuels, a gas field of 3 trillion cubic feet (500 mmscf/d for 20 years) would typically be required, Punt said. A world-scale GTL plant would produce some 60,000 b/d of hydrocarbons, selling into a 22 million b/d world middle distillate market. Such a full-size GTL plant would require an investment of between \$1 billion to \$1.5 billion, Punt said. A two-train GTL unit together with supporting infrastructure would require an investment of about \$25,000/bbl/day, a cost reduction by a factor of two compared to the Bintulu plant. Further savings could be realized by expanding an existing LNG complex with one or more GTL trains, saving infrastructure and support costs, he said.

-- Jack Peckham

**Exclusive On-Site Report:****Shell Bintulu Rising From The Ashes... (from p8)**

are especially good for feedstock for n-paraffins and PVC plasticizer manufacture;

- \* Kerosene, both for solvent uses and for trimming heavy gasoils to upgrade lower-quality stocks to specification diesel;

- \* Normal paraffins for detergent feedstocks. These C10-C13 molecules are used as intermediates in the production of detergents, especially in Asian markets where powdered kitchen detergents predominate;

- \* Ultra-clean diesel blendstock (such as for blending to meet California Air Resources Board diesel fuel standards). While CARB diesel is an initial market for SMDS gasoil, demand for the zero-sulfur, zero-aromatics, high-cetane diesel fuel is expected to grow. SMDS diesel also has been used for diesel blending in Asia;

- \* Candle and specialty waxes. Various forms of these waxes are used in particle board and MDF board manufacture, crayons, textiles, hot-melt adhesives, coatings, plastics processing, rubber compounding, printing inks and cosmetics.

**Pioneering Experience In the Technology**

On the long road leading to Bintulu, Pegels accumulated valuable experience with clean-fuels technology development, having started the first Shell fuel oil desulfurization unit in Japan at Seibu-Sekiyu. That project slashed fuel sulfur from 4% to 0.5%. Other steps on the path included 12 years at Shell Technologies in The Hague (Netherlands), then refining work in Curacao, Sudan and the Phillipines.

Having been at SMDS Bintulu from the beginning, he and his colleagues now represent an institutional body of knowledge about perhaps the world's leading-edge refining technology for future ultra-clean fuels. That experience could

translate not only into more Shell SMDS plants, but possibly other GTL joint-venture plants throughout the world.

"When we started here, the average worker at the Shell Pernis refinery [in Netherlands] had about four times the experience of the workers here. But since then, we've greatly improved our knowledge through a combination of experience of experience and training," Pegels said.

That experience, plus the work of outstanding GTL researchers at Shell Amsterdam since 1973 and top management commitment to the technology, explain the confidence Shell places in GTL, he said.



## Special Focus on GTL Diesel Ethers:

### Joint European Study Finds Benefits of FT Diesel

A multi-country study sponsored by the European Commission found that several diesel fuel reformulations can reduce emissions, with Fischer-Tropsch diesel and a Scandinavian biodiesel blend showing among the best results.

The study by Institut Francais du Petrole, Instituto Motori, Netherlands Road Vehicle Research Institute (TNO), Euron and VTT found that super-clean Fischer-Tropsch (F-T) diesel can reduce pollutants substantially.

A blend of Scandinavian City Diesel with 20% biodiesel (tall methyl ester, or TME) was good at reducing both particulates (PM) and nitrogen

oxides (NOx) when used in vehicles with exhaust gas recirculation (EGR).

The research partners reported their results at the Society of Automotive Engineers Fuels & Lubes Conference in Tulsa, OK, and in a paper (SAE 972966). The researchers used 12 fuels and six diesel engines of older and newer technology. The fuels were:

- J1: highly desulfurized baseline fuel (100 ppm sulfur, 51.2 cetane number);
- J2: fuel highly hydrotreated to less than 5% aromatics (0.6 ppm sulfur, 66.1 cetane);
- J3: Fischer-Tropsch fuel (1.2 ppm sulfur, 82.8 cetane number);

• J4: a blend of hydrodesulfurized straight run and hydrodesulfurized light-cycle oil (39 ppm sulfur, 49.8 cetane). This blend contained 10% di n-pentylether (DNPE);

• J5: hydrodesulfurized straight run with 12% DNPE (35 ppm sulfur, 62.6 cetane);

• J6: an oligomerization fuel mainly composed of isoparaffins (0.6 ppm sulfur, 35.4 cetane);

• J7: a 50-50 blend of J2 and J6 (1 ppm sulfur, 47.7 cetane);

• J8: a 50% blend of F-T fuel (J3) and J6 (0.8 ppm sulfur, 50.2 cetane);

• J9: a 40% blend of J3 and J6 (0.7

*(Continued, p8)*

### Ethers Could Cut 'Cleaner' Diesel Costs...(from p6)

The paper proposes R&D to find a balanced combination of options. This combination could include blending ether components upstream of mid-severity refining, possibly allowing less NOx and PM exhaust aftertreatment on a diesel engine.

Syngas-derived blend components and hydrogen for distillate desulfurization are both made from natural gas, the paper points out.

So, using these may also "lower global warming CO<sub>2</sub> and N<sub>2</sub>O from NOx catalytic aftertreatment," the analysis contends.

On related diesel ether research fronts:

• Ontario-based Advanced Engine Technology (AET) is pushing ahead with round-robin tests of its "Ignition Quality Tester" (IQT) cetane testing device, claimed to be far simpler, lower-cost and more accurate than the conventional cetane engine test. The

device, first developed by Southwest Research Institute (SwRI), has been modified by AET from manual to automatic operation.

This "combustion bomb" or "constant volume combustion apparatus" allows 15-minute, totally-automated cetane tests with only 15 milliliters of fuel.

#### Double Duty

The device not only could aid researchers evaluating ethers and high and low-cetane blendstocks, but also allow refiners to make real-time decisions on diesel blending, AET research engineer Gary Webster explains.

One device is in tests at Syncrude Canada, while another is in tests at Esso Research in the United Kingdom. A third device is scheduled to be shipped to Austrian refiner OMV for lab tests at University of Vienna, and another is to be evaluated at SwRI in

the U.S., Webster said.

AET aims to report results to American Society for Testing & Materials (ASTM) by December, and hopes to propose a final ASTM approval in 2000.

AET also developed a single-cylinder "small compression ignition engine emissions/fuel test rig" that can provide engine and emissions "screening test" evaluations for ethers and diesel fuels, he said.

• Diesel fuel's unpleasant odor could be modified by ethers with perfume-like qualities.

AET and NRCan are in discussions with one manufacturer of a diesel ether that improves cold-flow, boosts cetane, reduces emissions and improves fuel fragrance.

— Jack Peckham

## Special Focus on GTL Diesel Ethers:

### European Study Finds FT Diesel Benefit...(from p7)

ppm sulfur, 58.7 cetane);

- **J10:** a 40% blend J3 and J1 (75 ppm sulfur, 57.8 cetane);

- **J11:** Scandinavian City Diesel (23 ppm sulfur, 58.6 cetane);

- **J12:** 20% biodiesel, 80% J11 Scandinavian City Diesel (37 ppm sulfur, 53.8 cetane).

Test engines included both naturally-aspirated and direct-injection cars with and without oxidation catalysts and EGR, a medium-duty van, a heavy-duty truck engine and a heavy-duty bus engine. Tests were on the standard European cycles.

The different fuels and blends by themselves did little to reduce NOx emissions, although the low-density fuels produced lower NOx. That effect, especially noticeable at high loads, "could be attributed to the additional amount of fuel injected, cooling the combustion," the researchers concluded.

In both light-duty and heavy-duty engines, fuels of lower total aromatics and lower density (such as FT fuels and oligomerization fuels) consistently reduced PM, inorganic fraction (IOF), smoke, and polycyclic aromatic hydrocarbons (PAH).

#### Deep Hydro Effective

Among fuels showing other benefits, deeply hydrotreated fuel (J2) consistently outperformed hydrodesulfurized fuel. Hydrotreated outperformed hydrodesulfurized by 40% for CO, 40-60% for HC, and 20-30% for PM, depending on operating mode.

The low-cetane oligomerization fuel gave very low PM emissions — even lower than F-T fuel, mainly due to a low inorganic fraction content. But the fuel caused a big jump in soluble organic fraction (SOF) PM, especially under cold temperatures.

"Low cetane increases HC and consequently SOF emissions, but may have a beneficial influence on IOF by limiting the amount of fuel burning in diffusion regime," the researchers concluded.

FT blends "present good performance in terms of particulates, consistent with the low level obtained with both [pure] Fischer-Tropsch and oligomerization fuels," they said.

City Diesel with the TME biodiesel additive showed "the best potential for low emissions in presence of EGR due to the beneficial effect of oxygen on insoluble fraction of particulates," the researchers said. However, the biodiesel portion of the blend caused a 20% increase in CO and a

70% increase in HC. "The SOF emissions (like HCs) increase due to the drop in cetane number [compared to the base fuel] while the IOF tends to decrease because of the positive action of oxygen on soot formation," they said. Biodiesel also caused higher aldehydes, a function of increasing HC.

Fischer-Tropsch and oligomerization fuels and their blends gave the lowest PAH emissions. Notably, cetane number "clearly appears to be the only fuel parameter influencing CO or HC emissions," the research found. Fuel containing light-cycle oil "gives higher emissions, especially for particulates," the study found.

— Jack Peckham

## EUROPEAN FUELS SPECIFICATIONS

### Gasoline Maximum Limits

Parameter	Unit	Limits 2000	Limits 2005
Rvp (summer)	Kpa	60	—
Aromatics	Vol%	42	35
Benzene	Vol%	1	—
Olefins	Vol%	18	—
Oxygen	Wt%	2.7	—
Sulfur	ppm	150	50

### Diesel Fuel Limits

Parameter	Unit	Limits 2000	Limits 2005
Cetane Number	—	51 (minimum)	Auto-Oil II 1999 Decision
Density (at 15°C)	Kg/m3	845	Auto-Oil II 1999 Decision
95% Distillation	°C	360	Auto-Oil II 1999 Decision
Polyaromatics	% m/m	11	Auto-Oil II 1999 Decision
Sulfur	ppm	350	50

## Special Focus on GTL Diesel Ethers:

## Study Confirms FT Diesel Cuts Emissions in Real Vehicles

One of the few controlled studies of Fischer-Tropsch fuel used in actual on-road vehicles in the U.S. confirms that FT diesel cuts both nitrogen oxides (NOx) and particulate matter (PM) emissions, according to a study presented to the Society of Automotive Engineers.

The study (SAE 982526) tested FT diesel on seven White-GMC Class 8 heavy-duty trucks (1992 and 1994 model years) equipped with Caterpillar 10.3 liter engines, using West Virginia University's (WVU) unique transportable chassis dynamometer.

Compared to California Air Resources Board (CARB) diesel, the FT diesel cut NOx emissions 12%, PM emissions 24%, carbon monoxide 18% and hydrocarbons 40%, a five-mile test cycle showed.

Even a 50-50 blend of FT diesel with CARB diesel "reduced the NOx emissions from the trucks nearly as much as the neat FT diesel, but PM emissions were not reduced," the

researchers found.

The FT diesel, obtained from Shell-Bintulu (prior to an explosion 12 months ago), contained almost no sulfur, aromatics or olefins, and had a cetane number of over 74. A commercial lubricity improver was added to prevent injection system wear. However, the fuel wasn't upgraded via hydrocracking or isomerization in order to improve fuel cold-flow to the requirements of winter temperatures in cold latitudes.

Besides the lower emissions, "drivers could not detect a performance difference between trucks operating on FT diesel and a California diesel," the researchers from WVU, the National Renewable Energy Lab (NREL) and U.S. Department of Energy (DOE) found. However, the fuel economy penalty for FT diesel was about 3% compared to CARB diesel, as FT diesel has about 3 vol% less energy content. However, energy consumption in Btu/mile was nearly identical for both the CARB and FT diesels.

Encouraged by the results, the NREL/DOE/WVU research team continues with new tests of FT diesel in unmodified vehicles.

"Preliminary performance and emissions testing of older-model transit buses is underway to evaluate a gas-to-liquids middle distillate fuel synthesized using the Moss gas COD (conversion of olefines to distillate) process," explain NREL researchers Keith Vertin and Paul Norton.

"The study will compare exhaust emissions from 40-foot transit buses operating on U.S. federal No.2 diesel fuel, on Moss gas COD synthetic diesel fuel, and on a 50-50 blend of the two fuels."

These tests are on buses with unmodified Detroit Diesel 6V92 two-stroke engines. Emissions measurements will be performed on the standard CBD drive cycle using the WVU transportable chassis dynamometer.

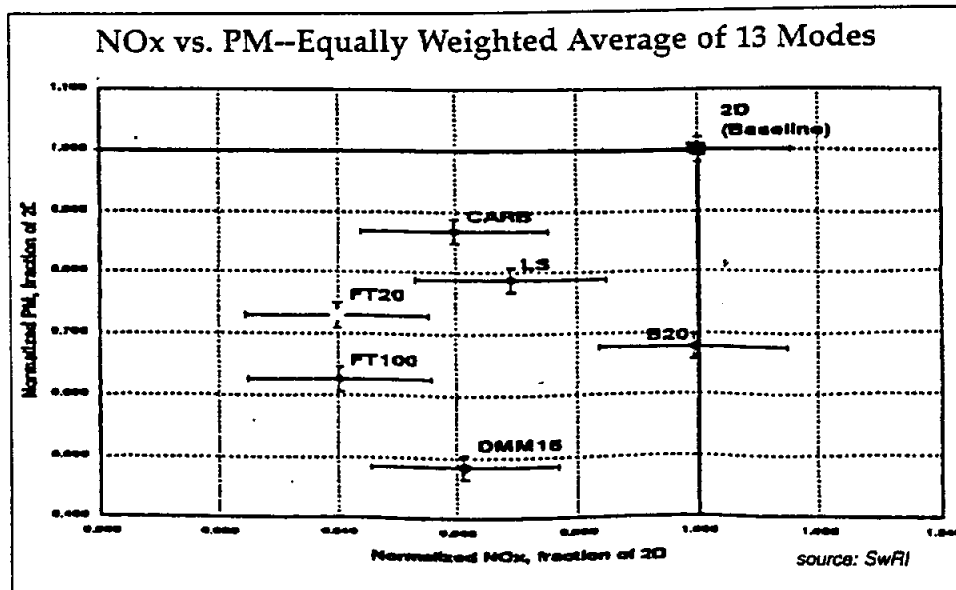
— Jack Peckham

## Energy Department Mulls Viability of DMM-Diesel Blends

San Francisco — At the Department of Energy, the jury is still out on whether methylal, a.k.a. dimethoxymethane (DMM) can play a significant role as a diesel blending agent.

DMM, although soluble in diesel and offering very low soot formation, has a lower heating value—about 20.2 megajoules/litre or about 0.55 of the energy density of diesel, said Keith Vertin, heavy vehicle team leader for DOE's National Renewable Energy Lab.

(Continued, p10)



## Fischer-Tropsch Diesel Cuts All Emissions, Unlike Biodiesel

Fischer-Tropsch diesel fuel not only reduces particulate matter (PM) emissions, but cuts *all* regulated emissions — unlike biodiesel, which reduces PM at the expense of increased nitrogen oxide (NOx) emissions, a new study shows.

That's especially important because most diesel emissions reduction schemes usually wind up cutting NOx by increasing PM, or vice-versa. This NOx/PM tradeoff is a bigger problem today because engine and vehicle makers are under heavy pressure from environmental regulators to cut both.

Researchers at West Virginia University reported these results in a study of a variety of diesel fuels, including real-world tests on a modern diesel engine running through the U.S. Federal Heavy Duty Engine Transient Procedure (FTP). Results were reported in a paper (SAE 1999-01-1117) to the recent Society of Automotive Engineers World Congress.

The engine tests on a 1994 emissions specification Navistar T444E

engine used U.S. EPA highway diesel, California Air Resource Board (CARB) diesel, various blends of soy-derived biodiesel, a Fischer-Tropsch diesel with ultra-low sulfur and aromatics, an FT fuel with ultra low sul-

fur but 10% aromatics, and the same FT fuel with 10 vol% isobutanol. The first 11 fuels in the chart (*below*) were tested by WVU; the other fuels were analyzed from literature.

(Continued, p19)

Table 2 Fuel properties [9,12].

Fuel Designation	Fuel Type	Density kg/l	Total Sulfur wt %	Cetane No.	Aromatics %	Oxygen Content %
Data from this study.						
Diesel A	100-road diesel	0.852	0.04	48.80	29.30	-0
BD20	80% diesel A and 20% BD	0.858	0.03	49.40	23.44	2.20
BD50	50% diesel A and 50% BD	0.868	0.02	50.30	14.85	5.50
BD100	100% Biodiesel (BD)	0.884	0.00	51.8	0.0	11.0
Diesel B*	149-states diesel	0.85	0.35	44	<30	-0
F-T	Malaysian F-T	0.7905	<0.05	73.7	0.1	-0
CA Diesel	California diesel	0.8329	0.01	53.7	18.1	-0
Diesel B*	149-states diesel	0.85	0.35	44	<30	-0
MG	Natural gas derived F-T	0.8007	<0.001	51.4	10.1	0
MG90/IB10	90% MG and 10% isobutanol	0.8016	<0.001	-48	9.0	2.20
MG50	50% MG and 50% diesel	0.8254	0.18	47.7	-20	-0
Data obtained from Graboski et al. [9].						
Graboski Diesel	149-states diesel	0.8468	0.031	48.2	34.3	0.21
Graboski BD20	80% diesel A and 20% BD	Not Reported	Not Reported	50.3	Not Reported	2.27
Graboski BD35	35% diesel A and 65% BD	Not Reported	Not Reported	52.2	Not Reported	4.00
Graboski BD65	65% diesel A and 35% BD	Not Reported	Not Reported	54.5	Not Reported	7.24
Graboski BD100	100% BD	Not Reported	0	56.4	Not Reported	11.03
Data obtained from Schaberg et al. [12].						
N	1Sasol Slurry Phase Distillate 1	0.7786	0.001	>73.7	2.68	-0
K	1Sasol Slurry Phase Distillate 2	0.7779	0.002	73.3	2.48	0.3
C	California diesel	0.8308	0.028	49.4	9.91	-0
2D	149-state diesel	0.8547	0.022	40.3	38.22	-0
B1	30% N and 70% 2D	0.8292	0.018	50.9	27.02	-0
B2	50% N and 50% 2D	0.8140	0.015	55.2	20.4	-0
B3	80% N and 20% 2D	0.7909	0.008	62.2	9.92	-0

\* Typical Base specification.

(1) Bold numbers represent actual values.

(2) Regular typeface numbers represent estimated values.

## 'Oxygenates' Cut PM, But Enviro, Cost Issues Remain

"Oxygenated" diesel fuels using ether additives or soy methyl ester (SME) show good potential for reducing particulate matter (PM) emissions from diesel exhaust, a recent study shows.

However, ethers may face heavier skepticism in the wake of California's new ban of MTBE from gasoline to avoid groundwater contamination. SME also faces a tough road because of its high cost, although "greenhouse gas reduction" might reduce "biodiesel's"

ban could cast a dark cloud on other potential fuel ethers.

"Yes it could, if the particular ethers [for diesel] are shown to have adverse health or other effects," said Boehman, director of the Combustion Laboratory at Pennsylvania State University. Several investigations are underway, and Penn State has contracted to begin a literature search on health effects of many ethers, he said.

As for the high costs of SME, Boehman cited a recent analysis by his Penn State students showing that SME could become more competitive with petrodiesel if SME production costs fall to \$1.55/gallon and if SME is allowed to earn carbon credits for

greenhouse gas emission reductions.

However, the student analysis also concedes that biodiesel still might continue to cost much more than petrodiesel — perhaps \$3.60/gallon, close to the price quoted to public bus companies now testing the fuel in the U.S. In that case, even with greenhouse gas credits, biodiesel still costs significantly more than U.S. petrodiesel, the analysis shows.

Meantime, in a separate test program on "oxygenates" impact on diesel exhaust emissions, Penn State and chemical producer Air Products & Chemicals found that several blends

(Continued, p18)

Gas-to-Liquids News asked Andre Boehman, one of the co-authors of the study, whether the MTBE

## FT Outperforms Biodiesel... (From p17)

"The biodiesel blends showed their ability to reduce PM, but at the expense of increasing NOx, following the simple argument that cetane enhancement led to earlier ignition," said the WVU researchers. "However, the Fischer-Tropsch fuels showed their ability to reduce all of the regulated

emissions."

The ultra-low-sulfur and aromatics FT fuel stood out among the crowd. Adding the alcohol to FT fuels further reduces NOx and PM compared to straight FT, but at the expense of increased hydrocarbon (HC) emissions, the tests showed. Biodiesel was

better than the straight FT fuels on HC reduction, too.

Results of three separate test runs, with the first run using various engine torque points, are shown in the table below. (Each of the three runs are separated by a heavy black line.)

— Jack Peckham

**Comparing Diesel Exhaust Emissions: FTP Tests on '94 Heavy-Duty Engine**  
(average of tests, in grams/brake horsepower-hour)

Fuel Type	HC	CO	CO <sub>2</sub>	NO <sub>x</sub>	PM
Off-road low-sulfur diesel	0.299	1.733	627.0	5.552	0.120
20% biodiesel	0.286	1.141	623.5	5.645	0.049
50% biodiesel	0.210	1.058	619.5	5.547	0.082
100% biodiesel	0.116	0.886	625.5	5.794	0.069
U.S. EPA diesel	0.346	1.584	643.7	5.373	0.120
FT Diesel- ultra-low sulfur/aromatics	0.198	0.968	611.5	4.607	0.104
CARB diesel	0.274	1.090	615.8	4.893	0.109
U.S. EPA diesel	0.446	1.476	626.0	5.460	0.122
FT Diesel 10% aromatics	0.407	1.285	623.6	5.105	0.103
Same FT diesel w/ 10% alcohol	0.538	1.442	586.2	5.077	0.094
50% FT/50% EPA diesel	0.398	1.389	613.6	5.161	0.110

Source: West Virginia University

## Venezuela Eyes GTL Projects... (from p16)

But PDVSA is also pursuing other ways to utilize those resources. Through a consortium with Iron, TransCanada Pipelines and the Venezuelan Tecnoconsult Group, it embarked on a \$450 million plan for the expansion of the eastern Venezuelan cryogenic complex known as ACCRO to increase natural gas

liquids (NGL) production by 40,000 b/d.

And at Jose, PDVSA Gas is involved in extensive investments—building new gas-to-ammonia and gas-to-urea plants that will increase its nitrogenized fertilizer production from 1.9 million tons to 4.6 million tons by the year 2000.

With its latest request through the TDA, it appears that among Venezuela's next moves might be an effort to implement the latest gas-to-liquids technology to manufacture clean diesel fuel and specialty products from the region's vast natural gas reserves.

—Jack Belcher



# *Natural Gas to Ultra-Clean Liquid Transportation Fuels*

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David Gray and Glen Tomlinson

Mitretek Systems

McLean, VA 22102, USA

Paper presented at the Gas-to-Liquids: Clean Fuels Strategy  
Conference held at Marble Arch Marriott Hotel, London, UK

16-18 Nov 1998

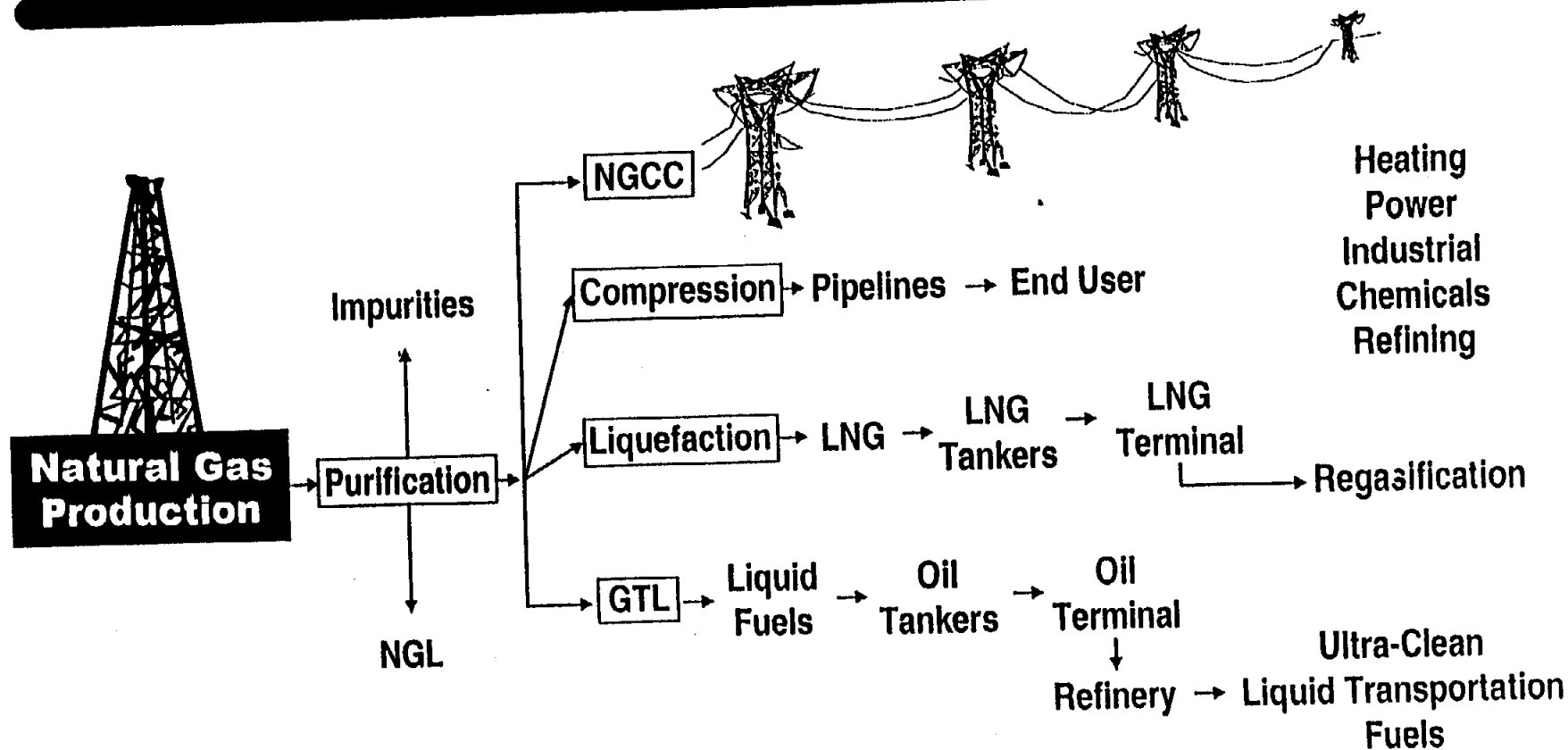
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# *Presentation Content*

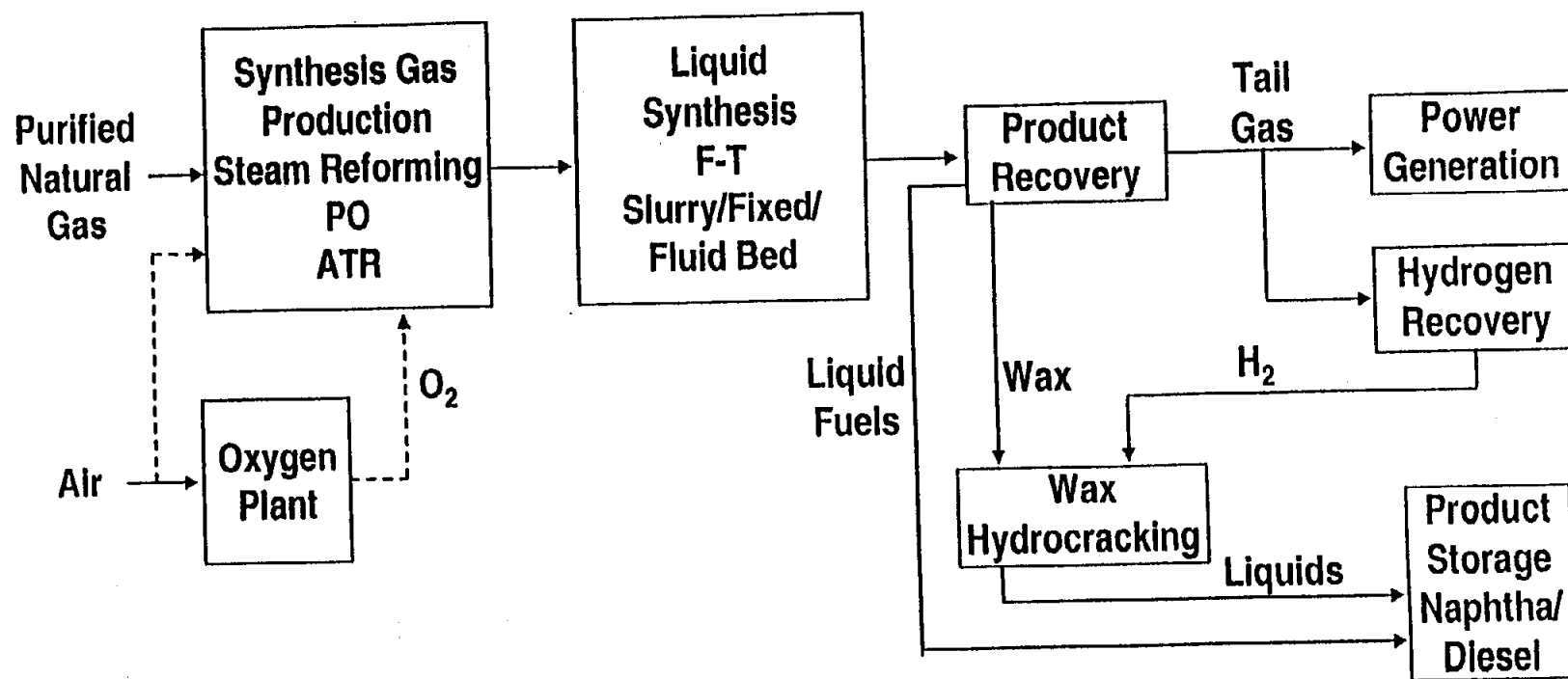
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- Overview of GTL technologies
- GTL vs LNG
- Overview of economics
- Does GTL really offer a clean fuels strategy?
- Potential risks of GTL
- Oxygen vs. air-blown systems for GTL
- Technical applications and future prospects

# Getting Natural Gas to Market



# ***GTL Technology: Overview***



# ***GTL vs. LNG***

Costs \$/MM Btu Feedstock	Capital	Operating	Transportation	Total	
LNG	0.53	1.71	0.54	0.74	3.52
GTL	0.83	2.15	0.72	0.10	3.80

## **Assumptions:**

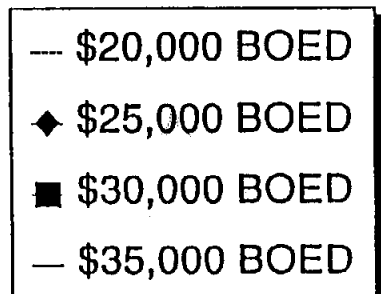
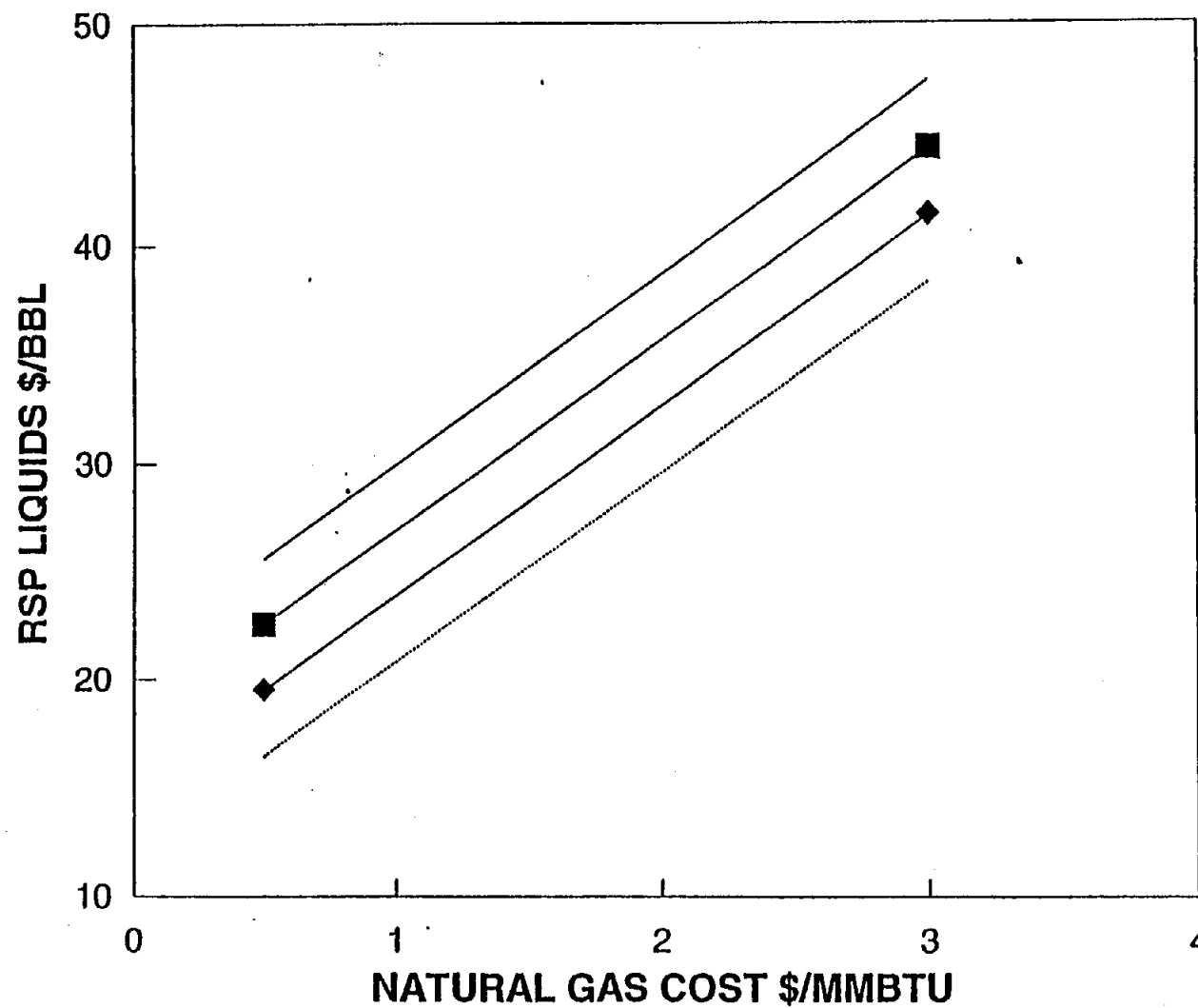
LNG - Capital \$14,100/daily barrel\* \$0.50/MM Btu NG feed

GTL - Capital \$25,000/daily barrel \$0.50/MM Btu NG feed

CRF 15%

\* based on capital cost of \$600 MM Liquefaction plant for a capacity of 1  
MMT LNG/year

## RSP OF GTL LIQUIDS AS FUNCTION OF GAS COST AND BOED



# *Is GTL a Clean Fuels Strategy?*

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**Emissions performance of synthesis gas-derived diesel fuels is superior to petroleum diesel fuels**

## **Emissions Reduction Relative to Low Sulfur Petroleum Diesel**

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Hydrocarbons	41-46%
CO	45-47%
NO <sub>x</sub>	9%
Particulates	27-32%

## **Emissions Reduction Relative to Low Sulfur/Low Aromatics Petroleum Diesel**

---

Hydrocarbons	25-31%
CO	34-38%
NO <sub>x</sub>	5%
Particulates	23-29%

# *Potential Risks of GTL*

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- Once built, the plant won't work properly!
- Even if it does work properly; you will still lose money!

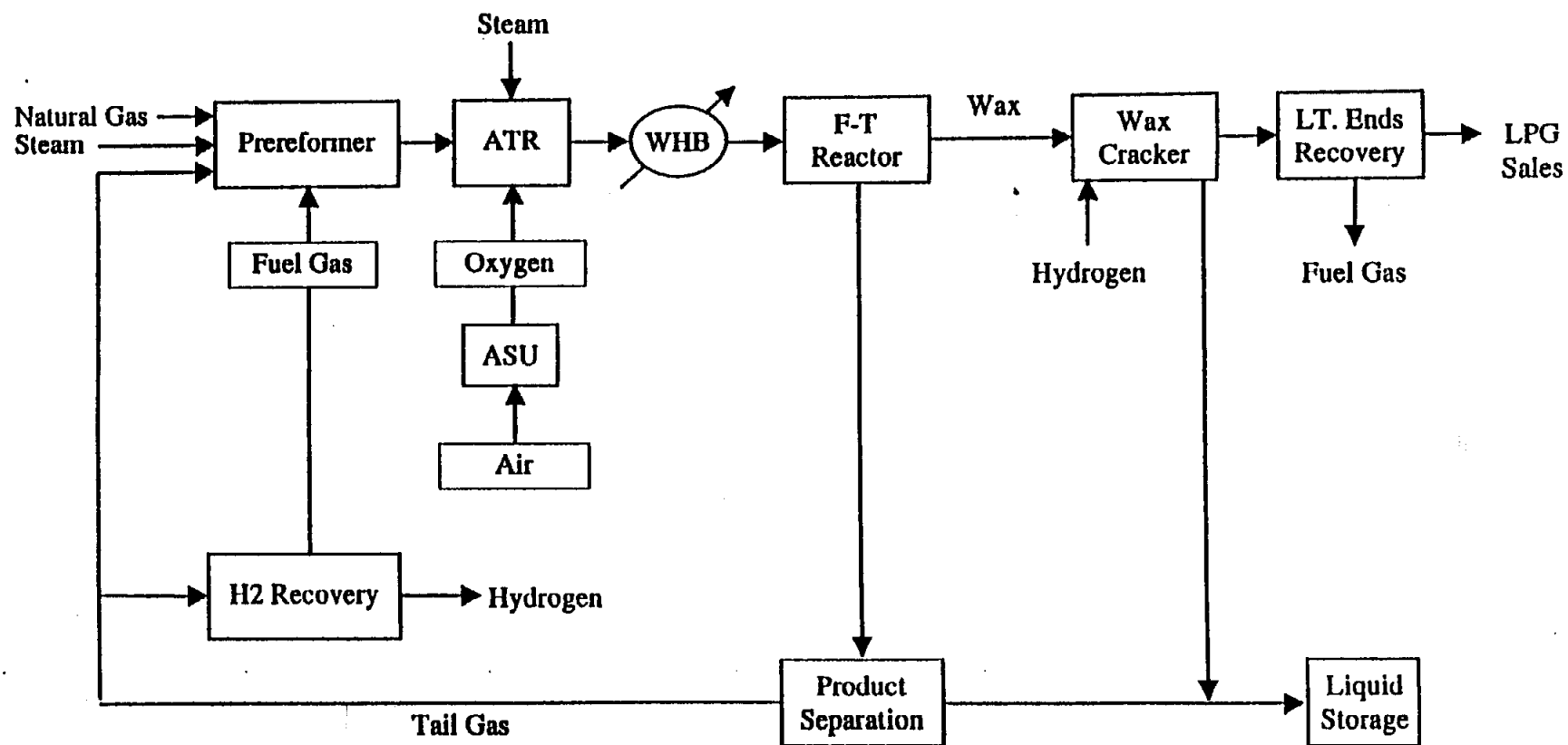


# *Technical Risks of GTL*

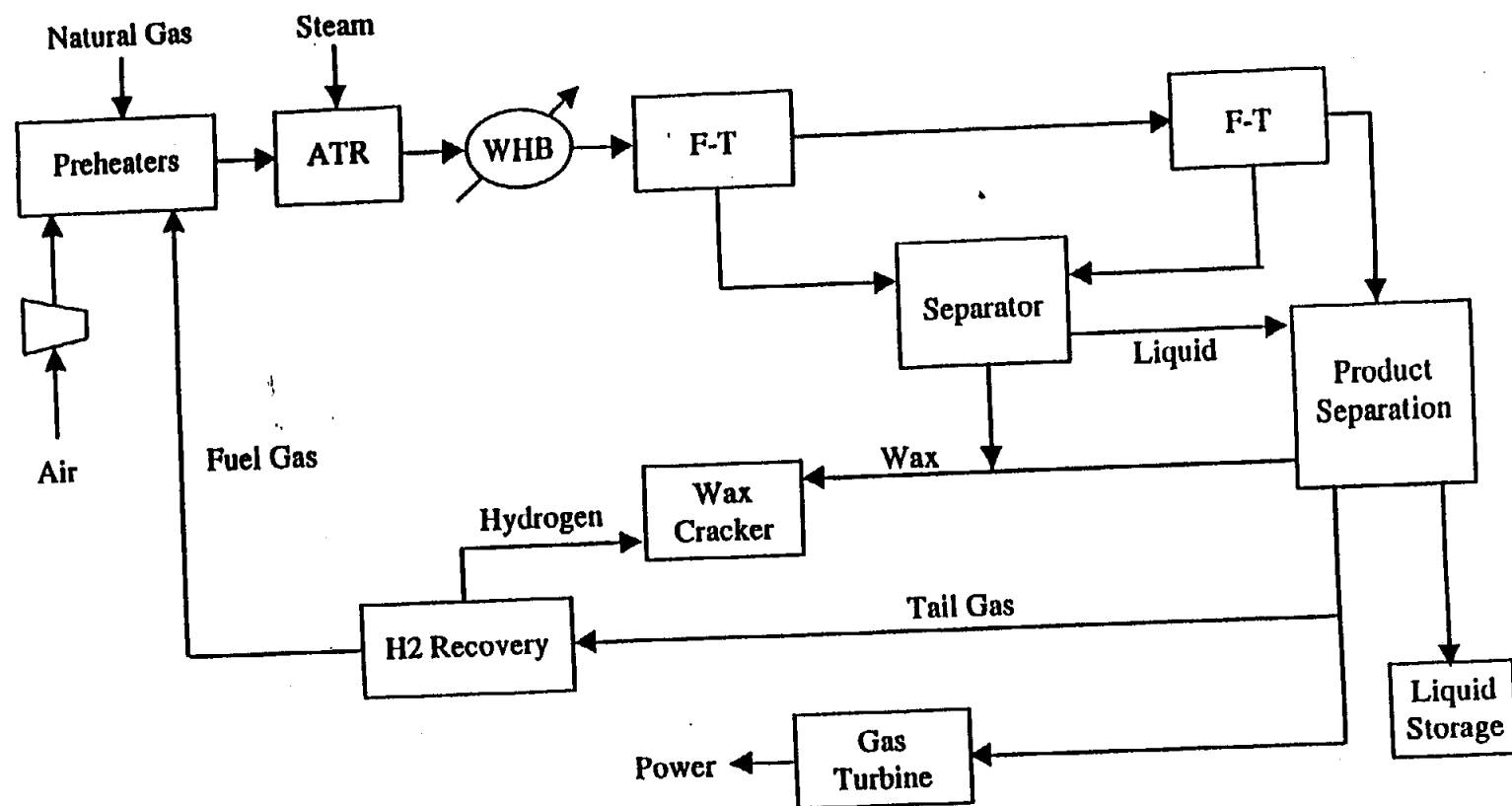
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- GTL technology is not really considered commercial practice
- Technical performance expectations may not be achieved
- Component integration must be demonstrated for high capacity factors
- Capital and operating cost expectations may not be realized (at least for first plants)

# *Oxygen-Blown GTL System Schematic*



# *Air-Blown GTL System Schematic*



# *Economic Risks of GTL*

---

- Future natural gas prices
- Future oil prices
- Value of the GTL product in the marketplace
- How long will stranded gas remain stranded (low cost?)

## **Next Step?**

- Commercial demonstration plant (reliable integrated operation)
- Incentives (host government) and industrial partnerships will be necessary

# *Technological Applications of GTL*

---

- Large Plants 50-100,000 BPD  
– large gas reserve > 7 TCF  
– integration with LNG facilities
- Small Plants 5-10,000 BPD  
– barge-mounted  
– small gas reserves  
– associated gas
- Impact of Future Technological Advances  
– improved synthesis gas generation (ionic transport membrane?)  
– improved synthesis gas conversion  
– cost reductions of the Nth plant

# **Diesel Technology Today & A Bit Beyond**

**Diesel Issues Forum  
April 14, 1999**

**Warren J. Slodowske  
Manager Environmental Staff,  
Navistar**

*Chair of Diesel  
Group at CVT*

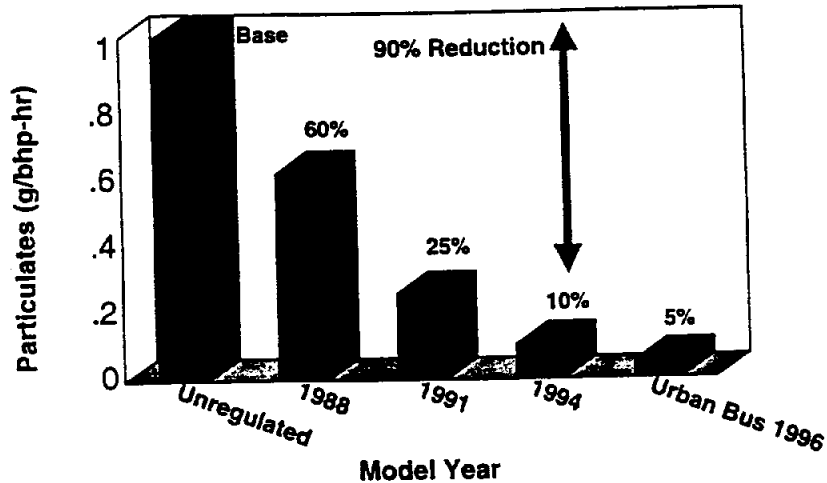
910-0942-00

## **The Technology Trail**

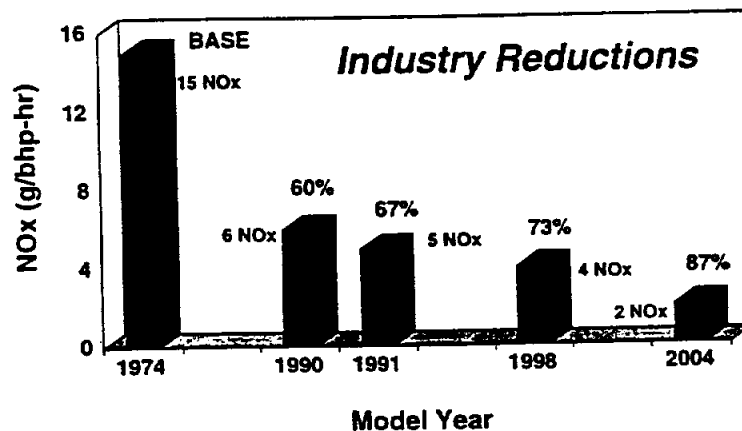
- **The Regulations Trail**
- **The 2004 Stringency Hit**
- **Technology Evolution Trail Through 2004**
- **The Next Technology Breakthrough**

910-0942-00

## Progress In Reducing HD Truck PM Emissions



## Progress In Reducing HD Truck NOx Emissions



## **EPA Proposal Adds Stringency to 2004 Regulation**

- **Requires compliance over a wider range of ambient conditions**
- **Requires Compliance over a wider range of engine operating conditions**
- **Requires Not To Exceed Limits ( Flatter Emissions Maps )**

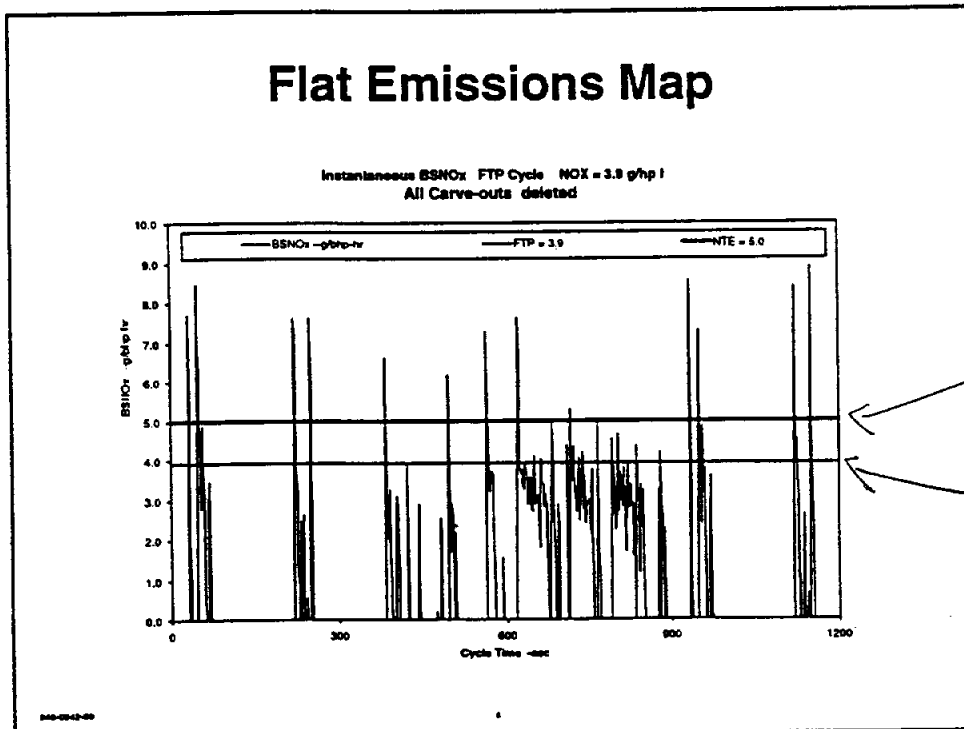
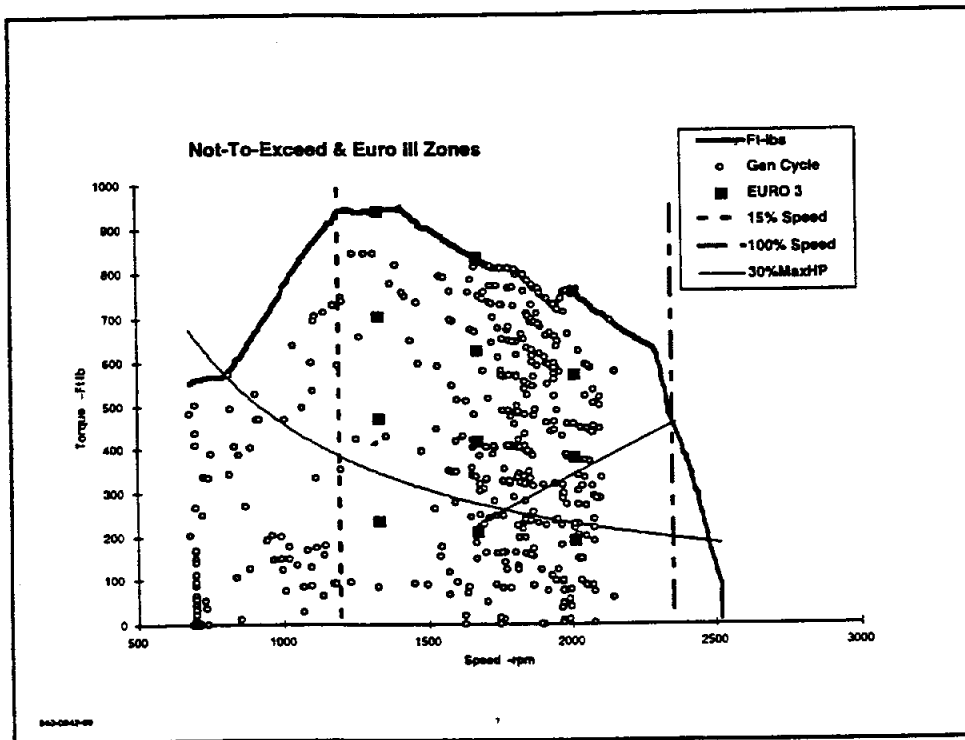
010-0842-00

## **Compliance Over Wider Range of Ambient Conditions**

- **No timing compensations for temperatures over 55°F**
- **No timing compensations for altitudes below 5,500 ft contrary to current practices.**

010-0842-00

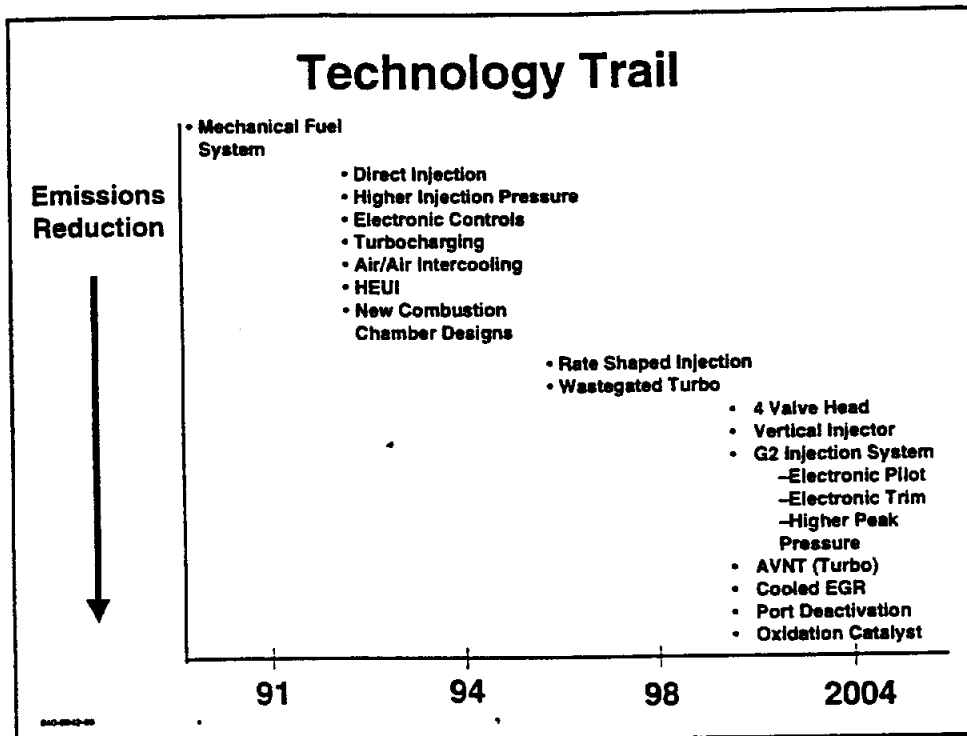




NOT TO EXCEED ~~15%~~ X STATION

NTE

CERTIFICATION LINE



## 4-Valve Head & Vertical Injector

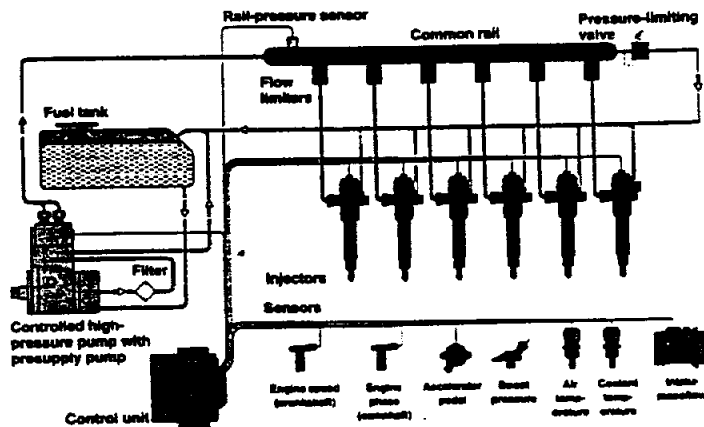
4-valve head allows the use of a vertical injector

This allows for a symmetrically spray pattern, better air motion control, & pulse injection

Enhanced Fuel Injection Control

910-0042-01

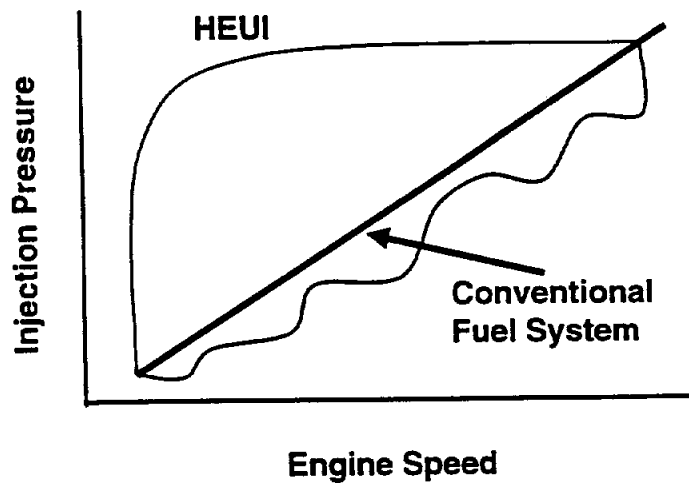
## G2/High Pressure Fuel Common Rail Comparison System Schematic



SAE-2012-01

11

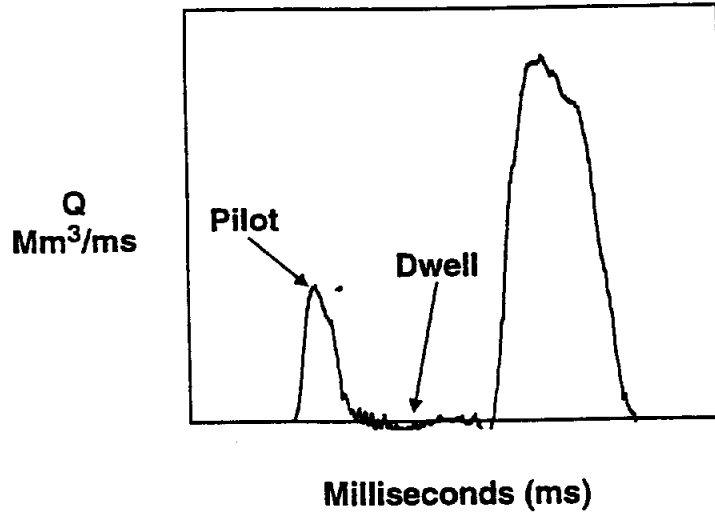
## HEUI & G2 Electronic Injection Pressure Control



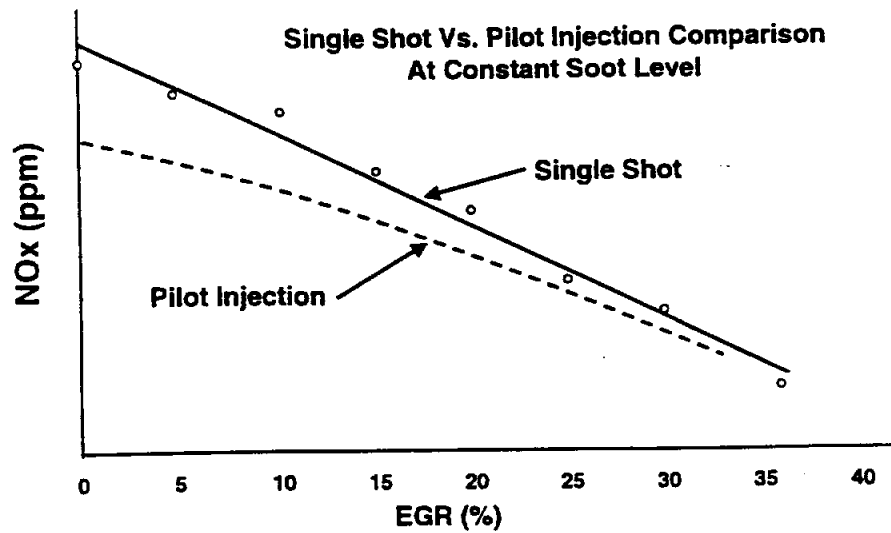
SAE-2012-01

12

## Rate Of Injection Trace



## Evolution Of G2 NOx Reduction As A Function Of EGR



*Advanced  
Variable  
Nozzle  
TURBO (AVNT)*

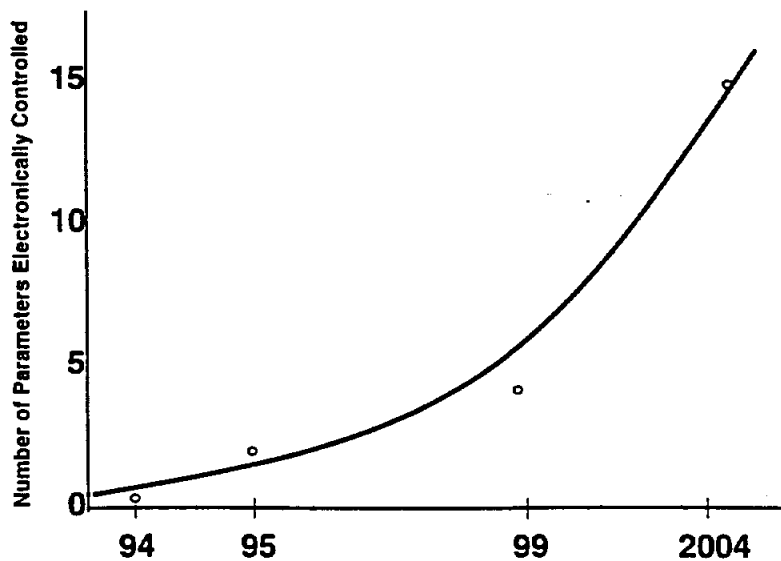
## AVNT (Turbo) & Port Deactivation

- AVNT allows for turbo boost variations independent of engine speed
- Port Deactivations serves as a variable swirl device

94-0843-01

11

## Evolution Of Electronic Controls



94-0843-01

12

## What does all this mean?

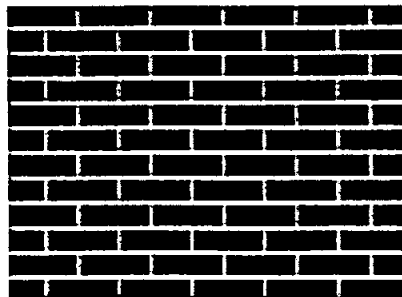
- We are close to the limit of reducing engine out emissions through the optimum electronic control of fuel delivery, of air delivery, of fuel/ air mixing, & of the combustion process.

040-0042-00

17

## The Barrier

- 2004 Truck compliance
  - HD problematic
  - LD unlikely
- Needs 30 ppm sulfur fuel



*Needs to meet  
Starts with*

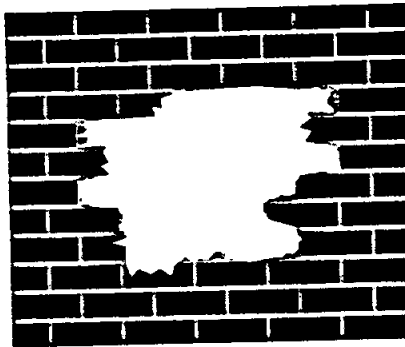
*Need better fuel*

040-0042-00

18

## The Breakthrough To The Next Level!

- The development of adv. Aftertreatment devices (Lean NOx catalyst & NOx Adsorber)
- We need ultra-low sulfur fuel
- Potential to achieve added 90% reduction of NOx & PM emissions



Winch  
Diesel &  
ET. Diesel

Priorities List  
- Sulfur  
- Aromatics  
- Cetane

# **Economics and Experience of Blending Fischer-Tropsch Diesel at Paramount Petroleum**

*~ presented by ~*

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## **Gas-To-Liquids Processing 99**

*May 17-19, 1999 • La Mansión del Rio Hotel • San Antonio, TX*



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# **Economics and Experience of Blending Fischer-Tropsch Diesel at Paramount Petroleum**

## **Background**

Paramount Petroleum Corporation (PPC) (Paramount, CA) and EOTT Energy (Long Beach, CA) are two of the California firms which have experience using Fischer-Tropsch (FT) diesel as a blending component in the manufacture of cleaner burning diesel fuel. These two firms worked together under a processing and marketing arrangement in 1995 when the FT blending began.

This paper will describe briefly the experience of PPC and EOTT and the requirements for producing California diesel fuel and the benefit and value of using FT diesel as a blendstock in making California diesel.

Due to its unique geography and population and the resulting environmental challenges these bring, the State of California has long been regarded as the leading edge for environmental legislation and regulation in the United States.

Beginning October 1, 1993, the California Air Resources Board <sup>1</sup> (CARB) required all diesel fuel sold in California to comply with new chemical composition requirements in Section 2282 of Title 13 of California Code of Regulations "Aromatic Hydrocarbon Content of Diesel Fuel".

Heavy-duty diesel engine (the type used by trucks and buses) emission testing indicated that there was a strong correlation between fuel qualities (particularly aromatic and poly-aromatic content) and NOx and particulate emissions from these engines.

Consequently, Section 2282 required most of the diesel sold in California to have maximum aromatic content of 10 percent (by volume) or produce the equivalent emissions of a 10 percent aromatic reference fuel. CARB granted an exemption to small refiners (less than 50,000 bbls/day crude capacity) allowing them to produce 20 percent aromatic diesel fuel up to CARB established production limits. This

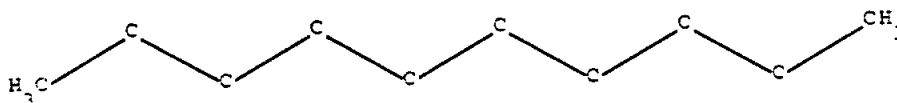
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<sup>1</sup>CARB is the state agency responsible for air quality, under the California EPA (the state agency responsible for environmental quality)<sup>1</sup>

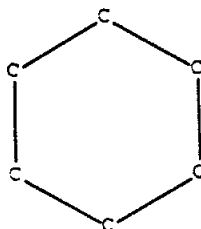
provision allowed small refiners to produce CARB diesel without new hardware by blending 10 percent aromatic fuel with low sulfur EPA diesel to produce additional CARB diesel.

### Diesel Chemistry

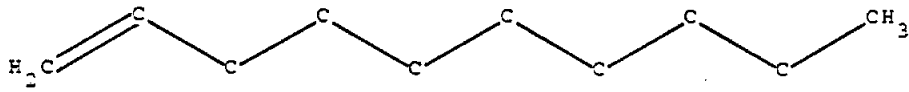
Diesel fuel is a mix of various hydrocarbon molecules with a boiling range of 400-650 Degrees F and with 10 to 20 carbon atoms. Aromatic is the generic term used to describe unsaturated (hydrogen deficient) cyclic (ring shaped) hydrocarbon molecules. The chemical figures below show examples of the four general classifications of organic compounds (in order of hydrogen deficiency), paraffins, naphthenes, olefins, and aromatics. The most simple aromatic compound is benzene (C<sub>6</sub>H<sub>6</sub>). If two or more aromatic rings are connected, it is called a poly-aromatic hydrocarbon (PAH). The naphthalene and biphenyl shown below are both examples of PAHs. Natural diesel in California has four to ten percent PAH content. These compounds are considered poor combustors and are the highest exhaust emissions producers of the aromatics compounds.



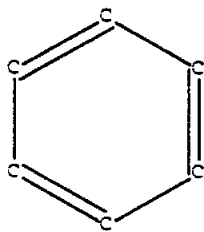
**Paraffin (decane)**



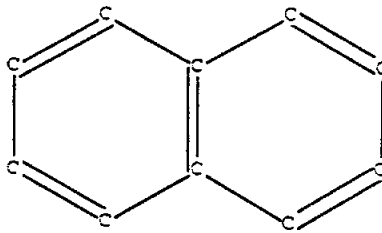
**Naphthene (cyclohexane)**



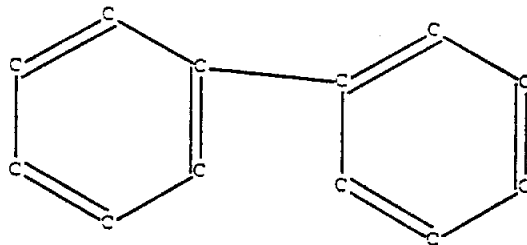
**Olefin (1-decene)**



**Aromatic (Benzene)**



**Poly-Aromatic (Naphthalene)**



**Poly-Aromatic (Biphenyl)**

The naturally occurring aromatic content in diesel fuel varies by both crude oil composition and the boiling range of the diesel fuel. The mix of crude oils commonly refined in California (local and Alaska North Slope (ANS)) produces diesel fuel that ranges from 25 percent to 35 volume percent aromatic.

To reduce the aromatics content of this "natural" diesel fuel to the specified 10 percent maximum requires reacting the aromatics in the fuel with hydrogen. Using benzene to describe as a simplified example of this process (benzene is in the gasoline boiling range rather than diesel), the benzene ( $C_6H_6$ ) could be reacted with hydrogen to produce any of a variety of  $C_6$  compounds such as 1,3, hexylene ( $C_6H_{10}$ , an olefin), cyclohexane ( $C_6H_{12}$ , a naphthene), or hexane ( $C_6H_{14}$ , a paraffin). All of these compounds have lower boiling points than the original benzene. To perform this hydrogenation process on diesel fuel at a refinery requires expensive hardware and operation, which includes producing hydrogen to react with the diesel. The refining industry has estimated these costs at about six cents per gallon of diesel produced.

On-road diesel (EPA diesel) in the United States is currently hydrotreated to reduce sulfur to .05 weight percent sulfur. However the additional equipment and hydrogen required to further hydrogenate diesel to saturate aromatic compounds is not generally available at refineries and requires a substantial capital investment.

FT diesel meets the specifications for EPA and CARB diesel as shown in Table A-1 of the Appendix.

### **History of FT Diesel Use in CARB Diesel Blending**

In early 1995 the Paramount Petroleum Corporation (PPC) Refinery (independently owned) was running under a contract processing arrangement with Enron Oil Trading and Transportation (EOTT). Since PPC was classified as a small independent refinery, the CARB diesel regulation Section 2283 allowed PPC to produce about 9,000 bpd of 20 percent aromatic diesel rather than 10 percent aromatic diesel.

The typical PPC diesel production was about 30 percent aromatics and PPC did not have the capital to build a new aromatic saturation unit (estimated at more than \$50 million). After a one year waiver from CARB, PPC's only short term option to

produce CARB diesel was to purchase 10 percent aromatics fuel which was available and blend in a 50:50 ratio with PPC production to make 20 percent aromatic diesel.

PPC however soon discovered FT diesel, which could be blended in a ratio of only 33:66 with PPC production diesel to make 20 percent aromatic CARB diesel.

Large refiners in California required a ratio of 66:33 FT diesel to low sulfur diesel to make 10 percent aromatic CARB diesel. An example of blending economics for small and large refiners is shown below:

### **CARB Diesel Blending Economics**

#### **Assumed Blending Component Costs:**

<u>Component</u>	<u>cents/gallon</u>	<u>Vol% aromatic</u>
EPA Diesel	50	30
FT Diesel	60	0
CARB Diesel	57	10

#### **CARB Diesel Blending Cost and Profit:**

<b>Small Refinery (20 % Aromatic)</b>	<u>Cost</u>	<u>Net Profit</u>
Using FT Diesel and EPA Diesel	53.3	3.7 cents/gallon
Using CARB Diesel and EPA Diesel	53.5	3.5 cents/gallon

#### **Large Refinery (10 % Aromatic)**

Using FT Diesel and EPA Diesel	56.7	.3 cents/gallon
--------------------------------	------	-----------------

In this example it is apparent that small refiners making a 20 percent aromatic diesel can blend CARB diesel more profitably than large refiners making a 10 percent aromatic diesel and can consequently pay a higher price for FT Diesel. This was the situation in early 1995 when Paramount Petroleum was purchasing FT diesel for blending. The FT diesel was brought into San Pedro (Los Angeles) Harbor irregularly by Petrodiamond (Mitsubishi subsidiary) in relatively small parcels of 60,000 bbls or less. During 1995 PPC purchased and blended about 150,000 bbls of FT diesel into CARB diesel. The limiting factors were FT diesel availability and price and the price differential between EPA diesel and CARB

diesel. The logistics of blending the FT diesel and the finished blend properties were both satisfactory. This FT diesel blending terminated when PPC finished the development of two alternative CARB diesel formulations. Other importers such as Astra Oil Company and refiners such as Tosco Refining Company continued in the FT diesel market in California until the Shell FT plant was shut down due to an explosion in late 1997.

### Alternative CARB Diesel Formulations

There is another part of the California diesel regulation which allows refiners additional formulation flexibility and has been increasingly utilized by both small and large refiners. All CARB diesel is manufactured by this alternative formulation method now. This is Subsection (g) *Certified Diesel Fuel Formulations Resulting in Equivalent Emissions Reductions* of Section 2282. This subsection allows refiners to produce CARB diesel using an alternative diesel formulation, if the fuel burns as cleanly as either a 10% aromatic "reference" fuel (for large refineries) or a 20% aromatic "reference" fuel (for small refineries). The emission equivalence must be tested by more than 40 engine tests with a heavy-duty diesel engine in a CARB approved laboratory.

When the CARB diesel regulation became effective in 1993, only a small fraction of the CARB diesel was manufactured using an alternative formulation as shown in the table below:

<b>CARB Diesel Market Supply</b>	<b><u>1993</u></b>	<b><u>1999</u></b>
10% Aromatic.	80%	0%
20% Aromatic	10%	0%
Alternative Formulation	10%	100%

The additional flexibility (and lower cost) provided by alternative formulations has encouraged all CARB producing refiners to use alternative formulations today. Table A-2 in the Appendix lists California refiners, refinery capacities (in bbls/day crude oil) and their alternative formulations. Most of these formulations are confidential. The formulations that are public are summarized in Table A-3 of the Appendix. Each of the fuel properties listed is a maximum specification, except cetane number which is a minimum specification. It is readily apparent that these formulations have higher aromatic content than the 10 percent limits of the originally prescribed CARB formulation. These formulations also have much

higher cetane numbers (50-59) than the 40-45 cetane number typical of normal EPA diesel fuel.

Chevron and Tosco/Unocal have patented their formulations as U.S. Patents 5,389,112 and 5,792,339 respectively. The Tosco patent is the most comprehensive and its claims are summarized in Table A-4 of Appendix A.

### **Cetane Blend Value of FT Diesel**

The cetane numbers required by the alternative formulations (51-59) are substantially higher than the natural cetane numbers of 40-45 cetane for California diesel. This requires additization by cetane improver. The most common cetane improver is 2-ethyl-hexyl nitrate which adds nitrogen to diesel as well as cetane numbers. ARCO's low nitrogen formulations require an alternative cetane improver without nitrogen such as t-butyl peroxide which is not commercially cost competitive and has stability concerns. The response of the diesel cetane number to these additives is non-linear with the volume of the additive used. Therefore larger cetane number increases require substantially more additive than smaller cetane number increases as shown in Figure B-1 in Appendix B. Figure B-2 shows the costs of cetane improver additive needed to achieve higher cetane numbers with a typical 43 cetane California diesel fuel.

The cetane number of FT diesel is higher than the upper reference fuel used in the cetane test (ASTM 672) and must be determined in a mixture. PPC estimated the cetane number at 80. Since FT diesel's cetane boost in a diesel blend is linear with volume, the value of FT diesel as a cetane boost increases with increasing cetane number. Figure B-3 displays the relationship between volume percent of FT diesel in a 43 cetane EPA diesel blendstock and the resulting cetane number of the mixture. Figure B-4 in Appendix B shows the value of FT diesel as a cetane booster alone for a refiner increasing cetane of EPA diesel to make a high cetane CARB diesel alternative formulation.

There is another potential market for FT diesel that will value the cetane boost provided by the FT diesel. This market is for blending EPA diesel by upgrading catalytic cracker light cycle oil (LCO) with very low cetane numbers (10-25). The economic value of FT in this role is difficult to quantify since LCO is not a fungible product traded in an open market. Most LCO currently is blended into

diesel in small amounts, heating oil, or No. 6 fuel oil. The analysis of this use is outside the scope of this paper and may be the subject of a future paper.

### **Aromatic Blend Value of FT Diesel**

Aromatic content and cetane number are highly correlated in diesel fuel (lower aromatics is correlated with higher cetane). The aromatic blend value of FT diesel varies depending on the formulation used in the production of CARB diesel. From the Tosco formulation TF-3, a target aromatic value of 22.5% provides a basis to determine the value of FT diesel as a CARB diesel blendstock. An example of the blending economics using this formulation and the same prices used in the previous blending economics example is shown below:

#### **TF-1 Tosco Alternative Formulation**

<b><u>Component</u></b>	<b><u>Percent</u></b>	<b><u>Vol % Arom.</u></b>	<b><u>Cetane No.</u></b>	<b><u>Price</u></b>
EPA	75%	30	43	50
FT Diesel	25%	0	80	60
Total	100%	22.5	52.3	52.5

Since the cetane number of the blend is greater than the required 50.7, no additional cetane improver is needed. The differential between CARB diesel and EPA diesel in the example above is ten cents per gallon. This differential drives the value of FT diesel as a CARB diesel blendstock. The actual differential varies with supply and demand market conditions of both EPA and CARB diesel and is displayed in Figure B-5. The blending value of the FT diesel is four times this differential, since one gallon of FT diesel can be blended with EPA diesel to produce four gallons of CARB diesel with this formulation. This value should be reduced by four cents per gallon of FT diesel to allow a blender/refiner a one cent per gallon of CARB diesel incentive. Actual blender/refiner incentives needed will vary. In the example above, the calculated FT diesel value would be  $50 + (60 - 50 - 1) * 4 = 86$  cents/gallon. The calculated FT diesel value using this methodology for the period 1993-1999 is shown in Figure B-6.

### **Effect of Crude Oil Price on FT Diesel Value**

Because crude oil price is the major feedstock cost in the manufacture of CARB diesel, the price of CARB diesel and also the value of FT diesel as a blendstock are related to this price. Figure B-7 shows the relationship of FT diesel blending



value to the common benchmark West Texas Intermediate (WTI) crude oil price. It is clear that there is a relationship between crude oil price and FT diesel value. Due to the scatter in the data, the regression equation that defines this relationship, has a low R squared (.48). With the crude oil price expressed in cents per gallon, the FT value has a 1.77 multiplier (x coefficient) of the oil price.

In summary, the blending value of FT diesel for blending CARB diesel depends on the alternative CARB formulation used and varies widely from 50 cents/gallon to over \$1.00 per gallon depending on three changing market variables – the crude oil price, the EPA diesel price, and the CARB diesel price.

# **Appendix A**

## **Tables**

# Table A-1 FT Diesel, EPA and CARB Diesel Specs

Shell MDS Gasoil					EPA Diesel Spec	EPA Typ.	Addn'l for CARB Diesel	Other Method for ASTM 976
Test	Units	Method	Spec	Typ.				
Density	Kg/m3	ASTM D1298	790 max	780				
Color		ASTM D1500	2.0 max	0		2		
Distillation		ASTM D86						
IBP	Deg F	ASTM D86	Report	394		370		
5%	Deg F	ASTM D86	Report	426				
50%	Deg F	ASTM D86	Report	520		545		
90%	Deg F	ASTM D86	662 F Max		540-640	630		
95%	Deg F	ASTM D86	Report	667				
EP	Deg F	ASTM D86	Report	676		695		
Sulfur	Ppm	ASTM D1288	500 Max	<3	500	400		ASTM D2622
Flash Point	Deg F	ASTM D93	190.4	190.4	125			
Pour Point	Deg F	ASTM D97	Report	19.4		15		
CFPP	Deg F	IP 309	Report	26.6	26*	20		ASTM D2500
Kin. Vis @104F	Mm2/sec	ASTM D445	1.8-5.8	2.8	1.9-4.1			
Water	%v	ASTM D95	.05 max		0.05			ASTM D2709
Sediment	%wt	ASTM D473	.01 max					
Aromatics	%v	ASTM D5186	Report	<.1	35 max	30	10 or 20	
Additives			Nil			Nil	CI typical	
Ash	%wt				0.001			ASTM D482
Copper Strip Corr.					No.3			ASTM D130
Cetane Number	Unitless			80	40 min			ASTM D613
Either								
Min Cetane Index	Unitless	ASTM D976	70 Min	75	40 min	44.5		
or Max Aromatics	%v				35			ASTM D1319
Ramsbottom Carb.	%wt				.35 max			ASTM D524

**TABLE A-2 CALIFORNIA REFINERIES**

<b>Large Refiners</b>			<b>Alternative Formulations</b>
<b>Company</b>	<b>Location</b>	<b>Capacity</b>	
ARCO	Carson	255,000	2
Chevron	El Segundo	258,000	3
	Richmond	225,000	
Exxon	Benecia	128,000	0
Mobil	Torrance	130,000	2
Shell	Martinez	155,200	1
Texaco	Bakersfield	57,760	6
	Wilmington	91,675	
Tosco/Unocal	Martinez	156,000	4
	Wilmington	118,750	
	San Francisco/ Santa Maria	103,645	
<b>Total</b>		<b>1,679,030</b>	
<b>Independent Refiners</b>			<b>Alternative Formulations</b>
<b>Company</b>	<b>Location</b>	<b>Capacity</b>	
Ultramar	Wilmington	68,000	0
<b>Small Refiners</b>			<b>Alternative Formulations</b>
<b>Company</b>	<b>Location</b>	<b>Capacity</b>	
Paramount	Paramount	42,200	2
Kern County Refinery	Bakersfield	21,400	3
San Joaquin	Bakersfield	18,000	0
Sunland	Bakersfield	15,000	0
Huntway	Benecia	8,400	0
	Wilmington	5,500	0
Anchor Refining	McKittrick	10,000	0
Santa Maria Refining	Santa Maria	10,000	0
Witco Corp.	Oildale	9,785	0
Lunday-Thagard Oil	South Gate	7,000	0
Ten By Inc.	Oxnard	4,500	0
<b>Total</b>		<b>151,785</b>	

**TABLE A-3 Public 10% CARB Diesel Alternative Formulations**

<u>Company</u>	<u>Source</u>	<u>Date</u>	<u>Name</u>	<u>Arom.</u> <u>Vol%</u>	<u>Poly</u> <u>Wt%</u>	<u>Cetane</u>	<u>Nitrogen</u> <u>ppmw</u>	<u>Sulfur</u> <u>ppmw</u>
Chevron	EO G-714-001	29-May-92	D4781	19.0	2.2	58.0	484	54
Chevron	EO G-714-003	02-Dec-92	F2	19.0	4.7	59.0	466	196
Chevron	EO G-714-006	29-Jun-93	G2	15.0	3.6	55.0	340	200
ARCO	EO G-714-007	19-Jul-93	D-25	21.7	4.6	55.2	20	33
ARCO	EO G-714-008	19-Jul-93	D-26	24.7	4.0	56.2	40	42
Tosco/Unocal	EO G-714-012	28-Jan-94	TF-1	23.2	6.3	55.6	893	487
Tosco/Unocal	EO G-714-013	15-Mar-94	TF-3	22.7	8.6	50.7	1050	496

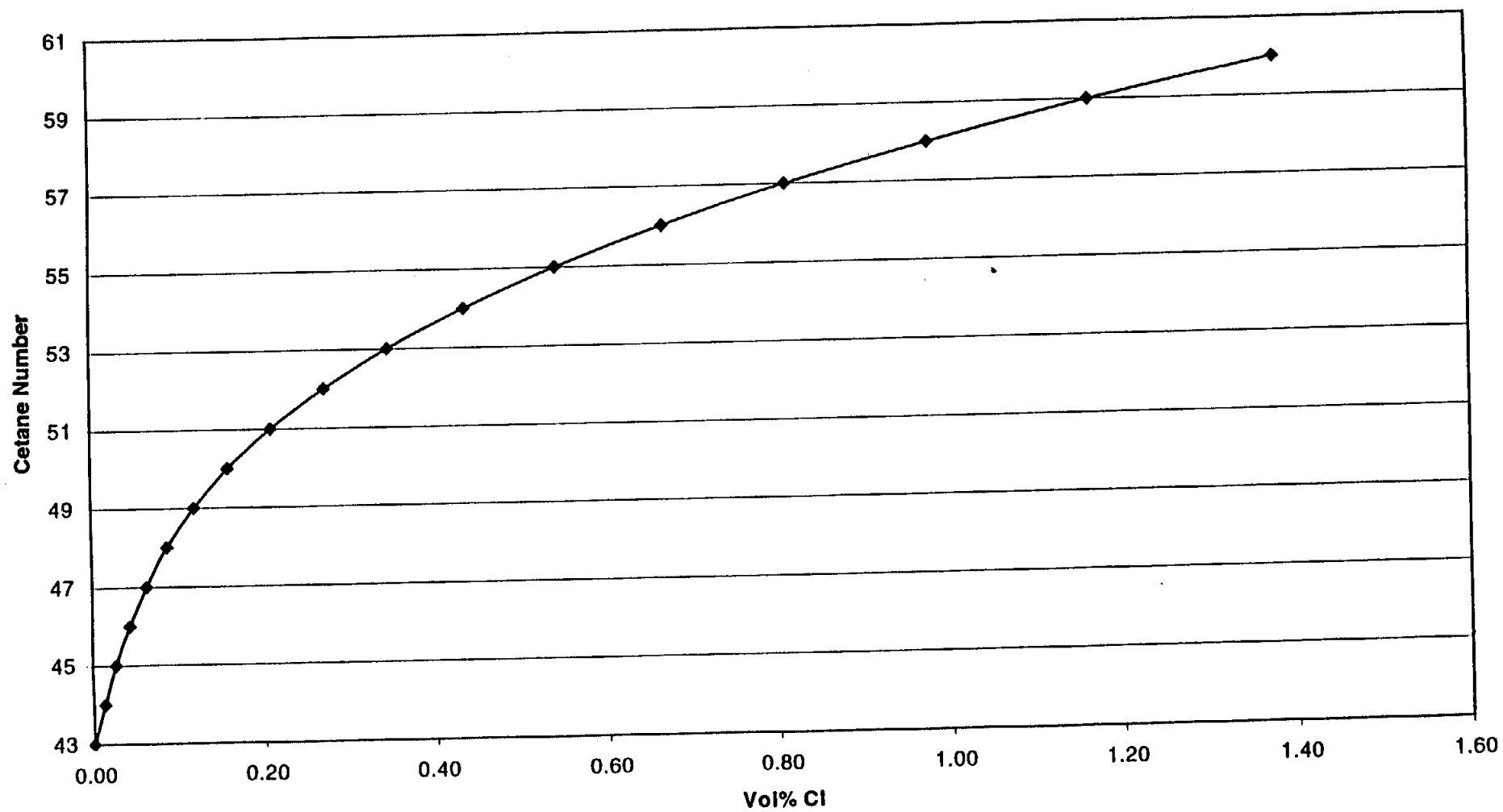
**TABLE A-4**  
**Tosco Patent Claims for CARB Diesel Formulations**  
**USPT 5,792,339**

<u>Claim</u>	<u>General Description</u>	<u>Poly</u>	<u>Nitrogen</u>		<u>Sulfur</u>
		<u>Wt%</u>	<u>Cetane</u>	<u>ppmw</u>	<u>ppmw</u>
1	Aromatics 10-23.9wt%, CN>50.7 + 1 of the following	5-8.6	50.7-54	500-1050	250-495
2	Claim 1 +2 of the following	>5.0	<54	>500	>250
3	Claim 1 +1 of the following	>5.5	<53	>600	>300
4	Claim 1 +1 of the following	>6.0	<52	>700	>400
5	Aromatics 15-23.9wt%, CN>50.7 + 1 of the following	5-8.6	50.7-54	500-1050	250-495
6	Claim 5 +2 of the following	>5.0	<54	>500	>250
7	Claim 5 +1 of the following	>5.5	<53	>600	>300
8	Claim 5 + 1 of the following	>6.0	<52	>700	>400
9	Aromatics 20-23.9wt%, CN>50.7 +1 of the following	5.0-8.6	50.7-55	500-1050	250-495
10	Claim 9 +2 of the following	>5	<55	>500	>250
11	Claim 9 + 1 of the following	>5.5	<54	>600	>300
12	Claim 9 + 1 of the following	>6.0	<53	>700	>400
13	Claim 9 + 1 of the following	>6.5	<52	>800	>450
14	Any Claim 1,3,4,5,7,8,9,11,12,13 having 2 properties				
15	Claim 14 with a nitrogen containing cetain enhancer				
16	Any Claim 1-13 having 3 properties				
17	Any Claim 1-13 having 4 properties				
18	Aromatics 10-23.9wt%, CN 50.7-55 +1 of the following	5.0-8.6		500-1050	250-495
19	Aromatics 15-23.9wt%, CN 50.7-55 +1 of the following	5.0-8.6		500-1050	250-495
20	Aromatics 16-23.9wt%, CN 50.7-55 +1 of the following	5.0-8.6	50.7-55	500-1050	250-495
21	Produce, deliver and dispense fuels in Claim 1,2,5,6,9,10,18,19,20				
22	Claim 21 producing >250,000 gallons/day over 4 week period				
23	Claim 21 produce, deliver, and dispense substantially over 1 week period				
24	Claim 21 produce, deliver and dispense substantially regularly over 4 week period				
25	Claim 21 produce and deliver >500,000 gallons/day over 1 week period				
26	Claim 21 produce, deliver, and dispense >750,000 gallons/day over 4 week period				
27	Claim 21 produce or deliver or dispense >250,000 gallons				
28	Operate a ground transport vehicle with fuel in Claims 1-13 or 18-20				
29	Operate a ground transport vehicle with CA 10% aromatics reference fuel equivalent emissions, fuels 1-13, or 18-20				
30	Operate a ground transport vehicle with CA 10% aromatics reference fuel equivalent emissions, fuel 16				
31	Operate a ground transport vehicle with fuel in Claim 14				
32	Operate a ground transport vehicle with fuel in Claim 15				
33	Operate a ground transport vehicle with CA 10% aromatics reference fuel equivalent emissions, fuel 17				
34	Claim 21 with distribution in California				
35	Claim 34 produce and deliver >500,000 gallons/day over 1 week period				
36	Fuel in Claims 1,5,9 or 18 whose emissions meet CARB protocol test equation				

# **Appendix B**

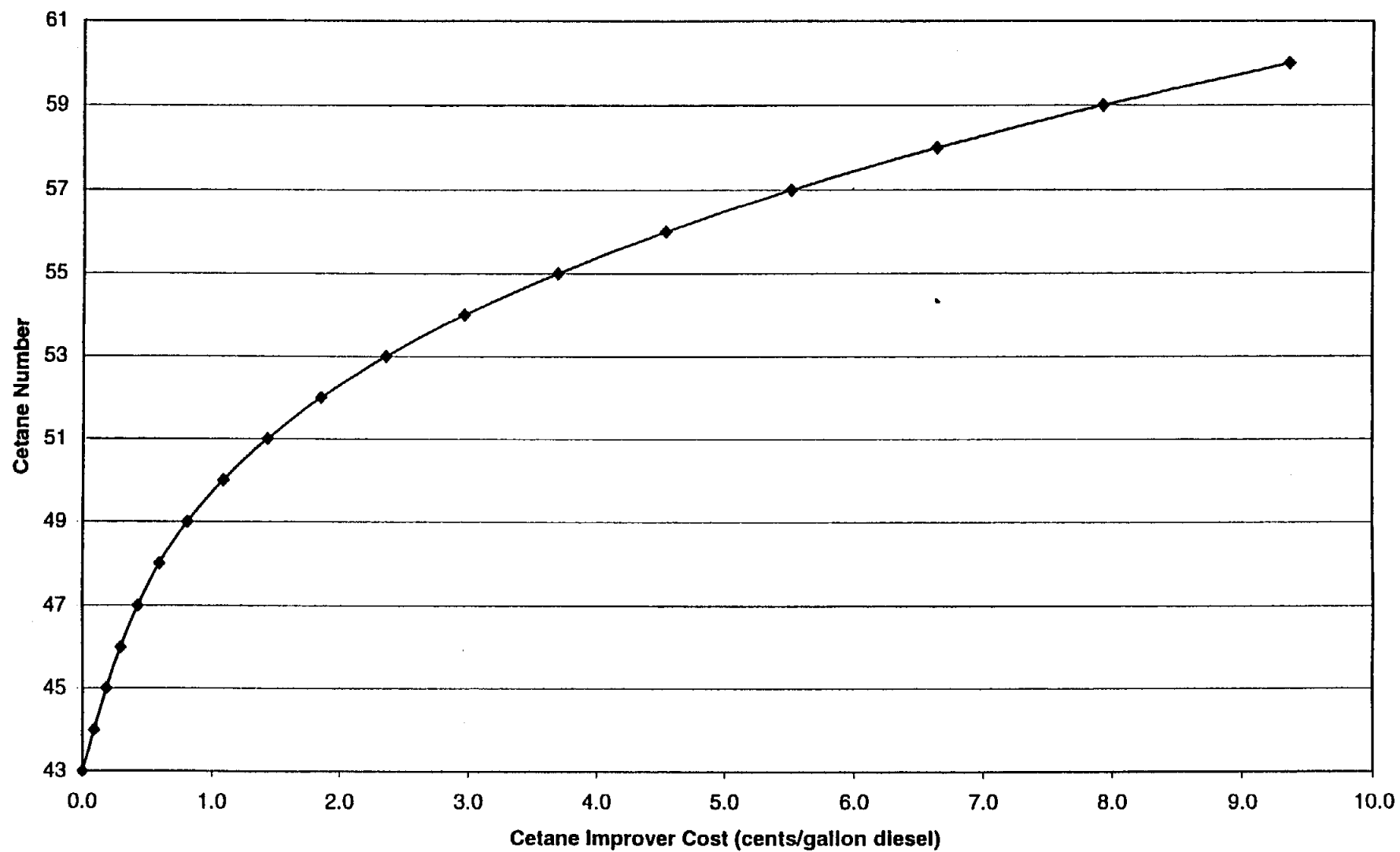
## **Figures**

**FIGURE B-1**  
**Vol% Cetane Improver vs Cetane Number**



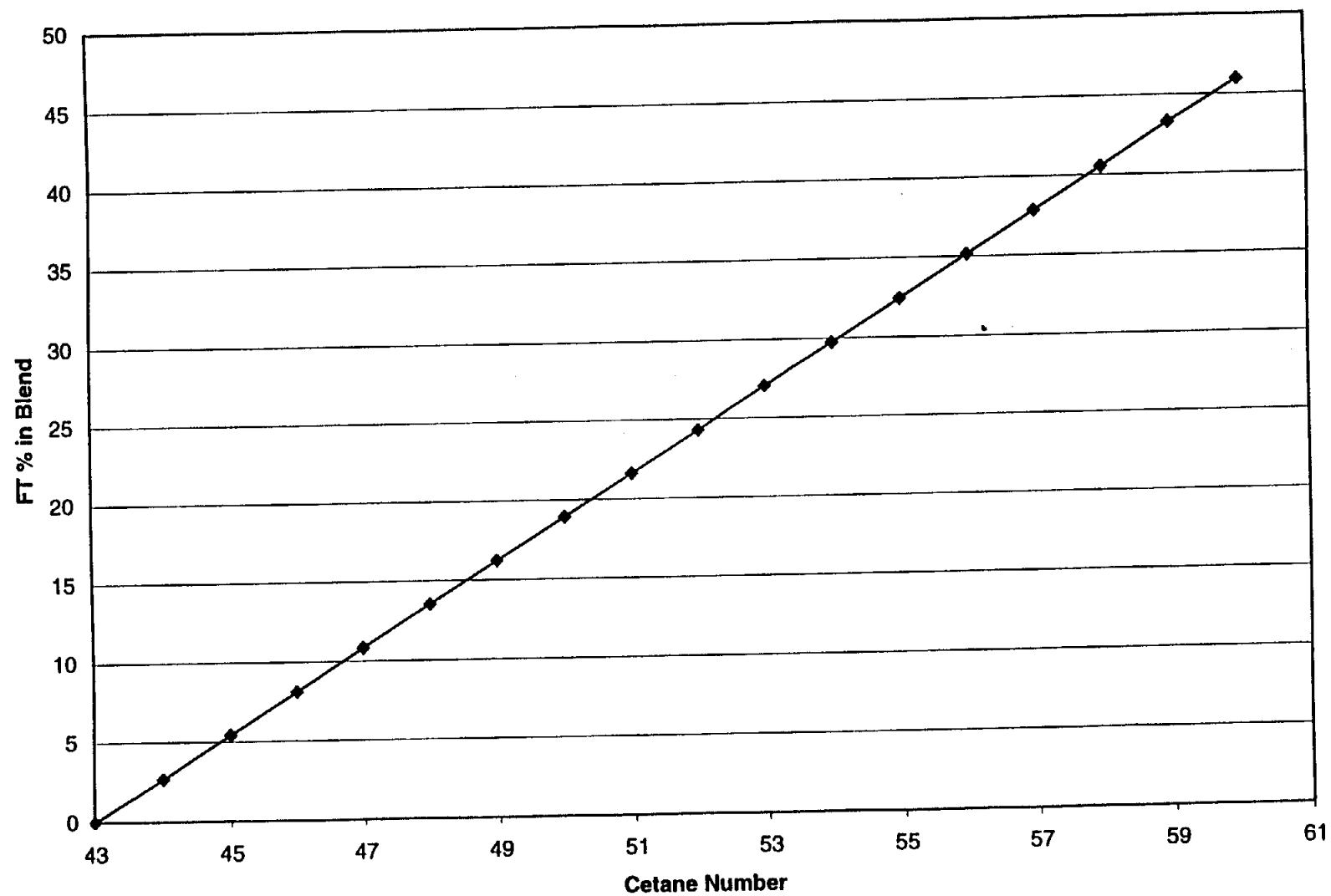


**FIGURE B-2**  
**Cetane Improver Cost vs Cetane Number**



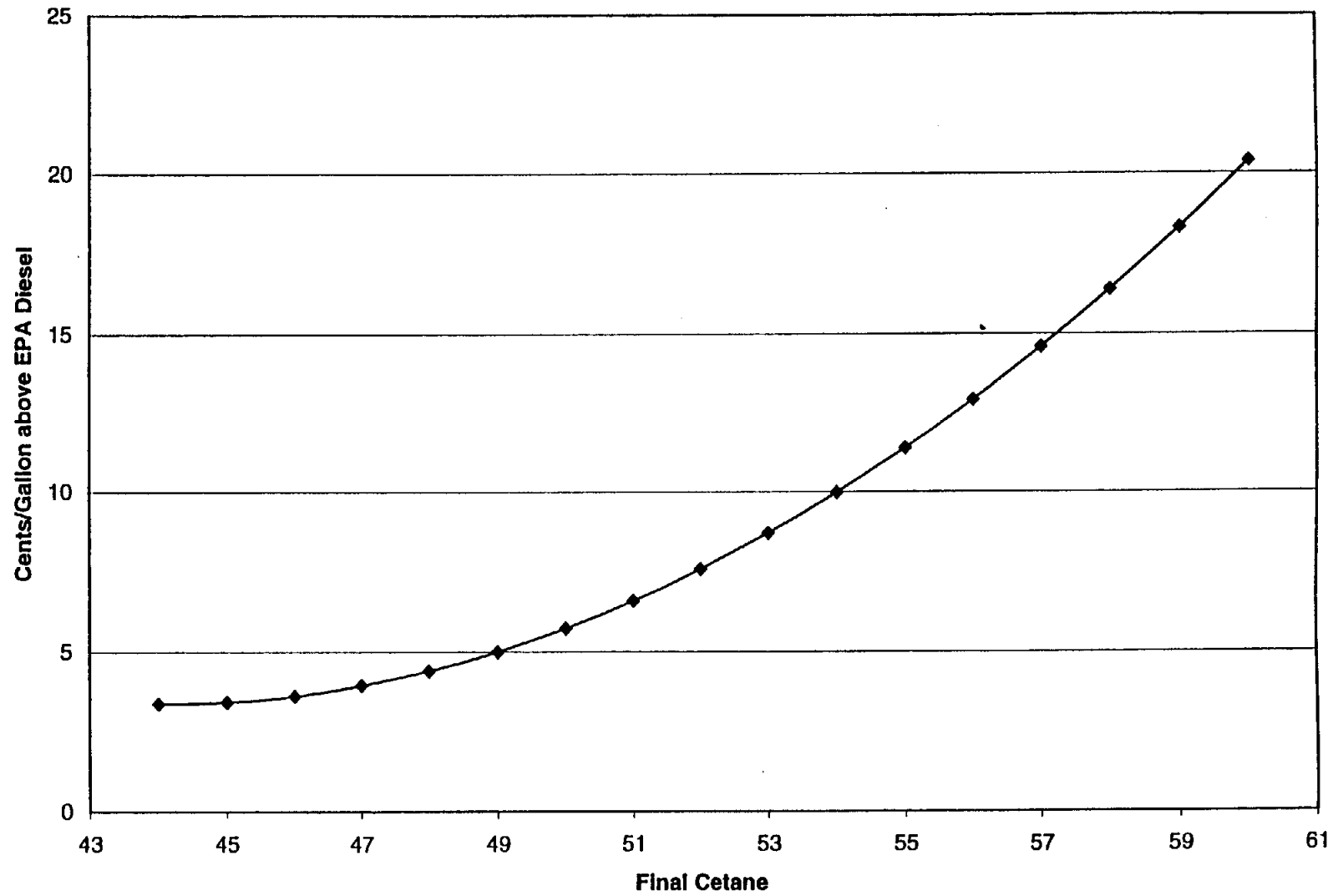
# FIGURE B-3

Cetane Number vs FT Percent in Blend

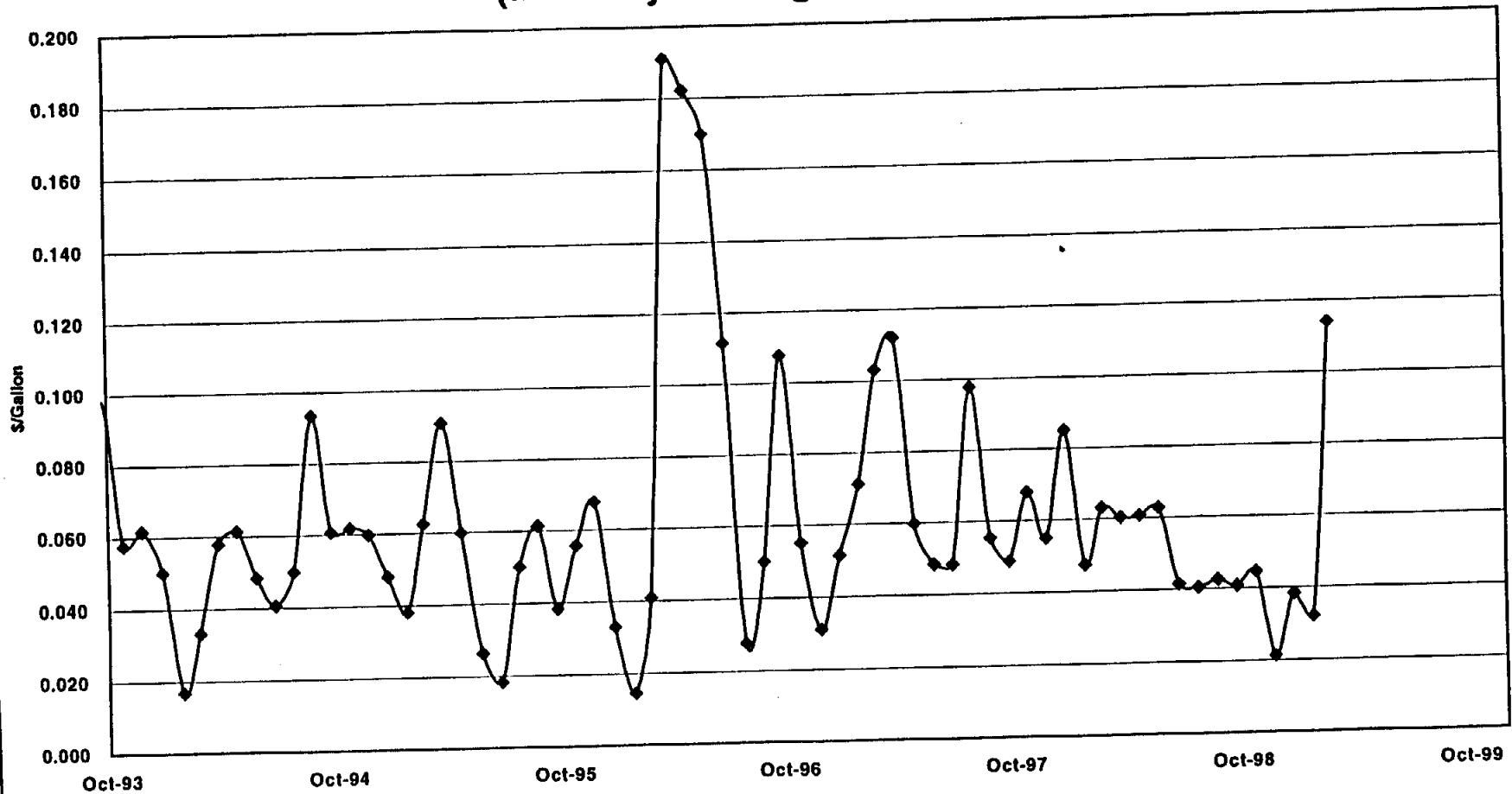


**FIGURE B-4**

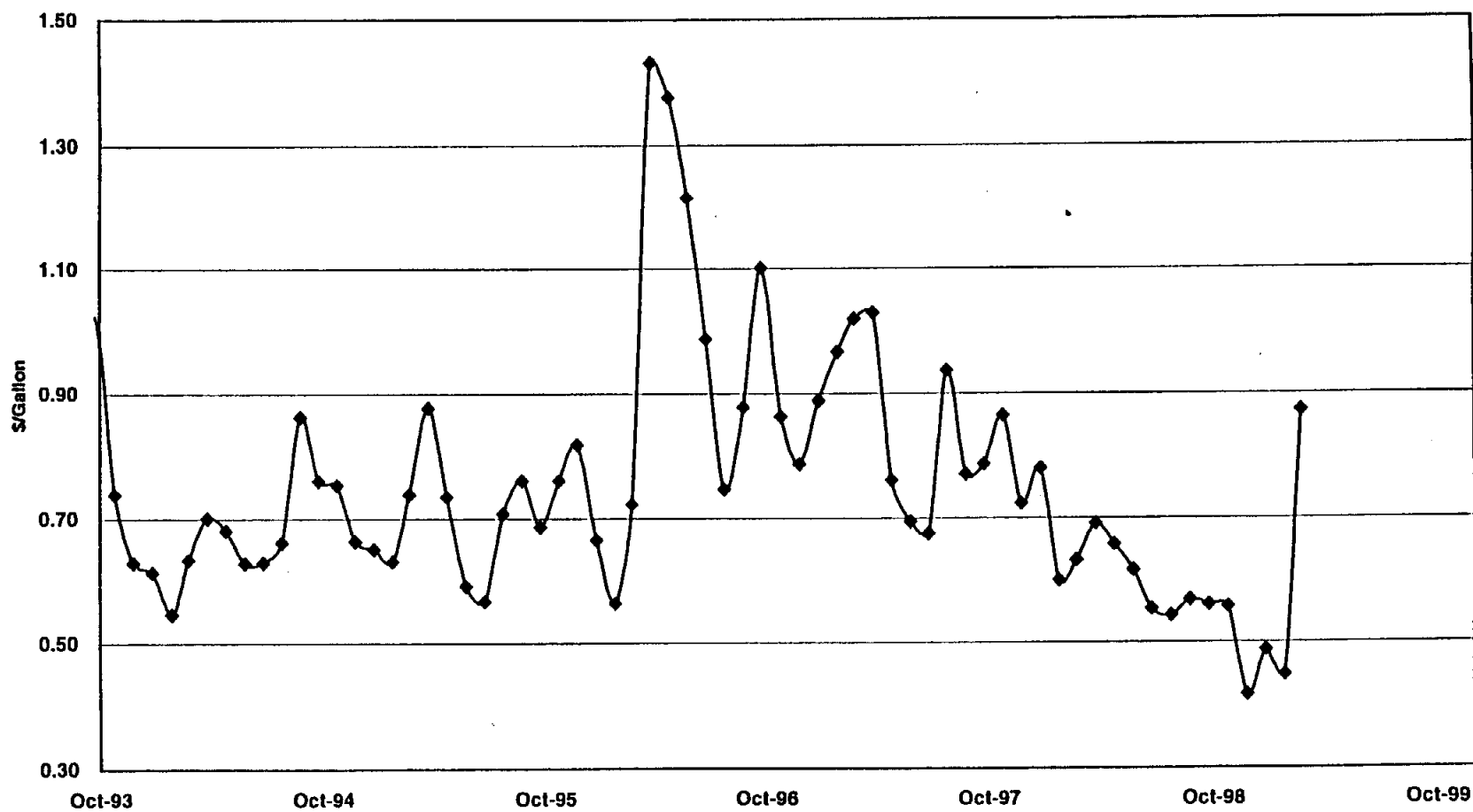
**FT Value above EPA Diesel as Cetane Improver**



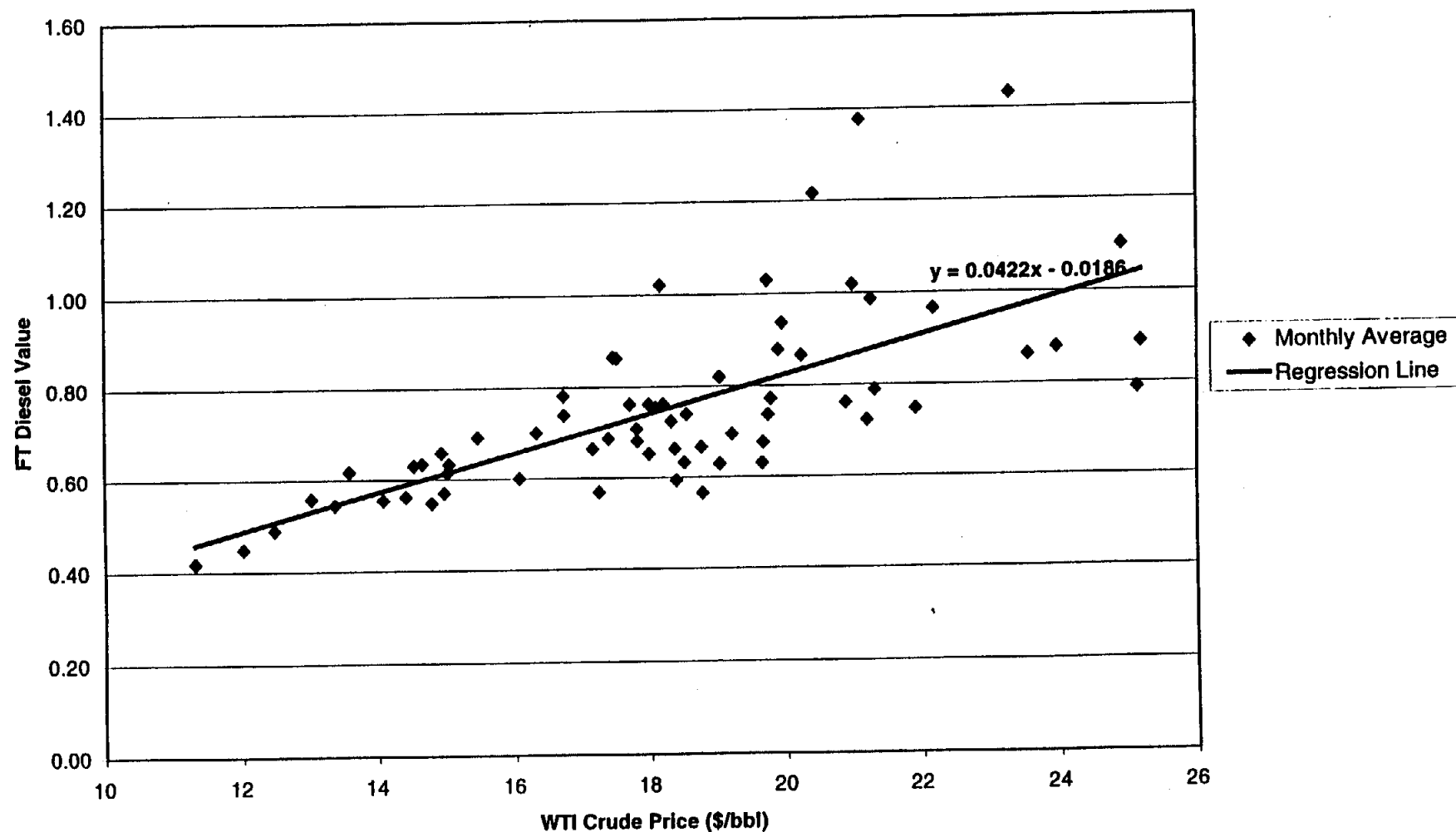
**FIGURE B-5**  
**CARB Diesel - EPA Diesel Price Difference**  
**(Monthly Average - \$/gallon)**



**FIGURE B-6**  
**FT Diesel Blend Value in CARB Diesel**  
**(Monthly Average - \$/gallon)**

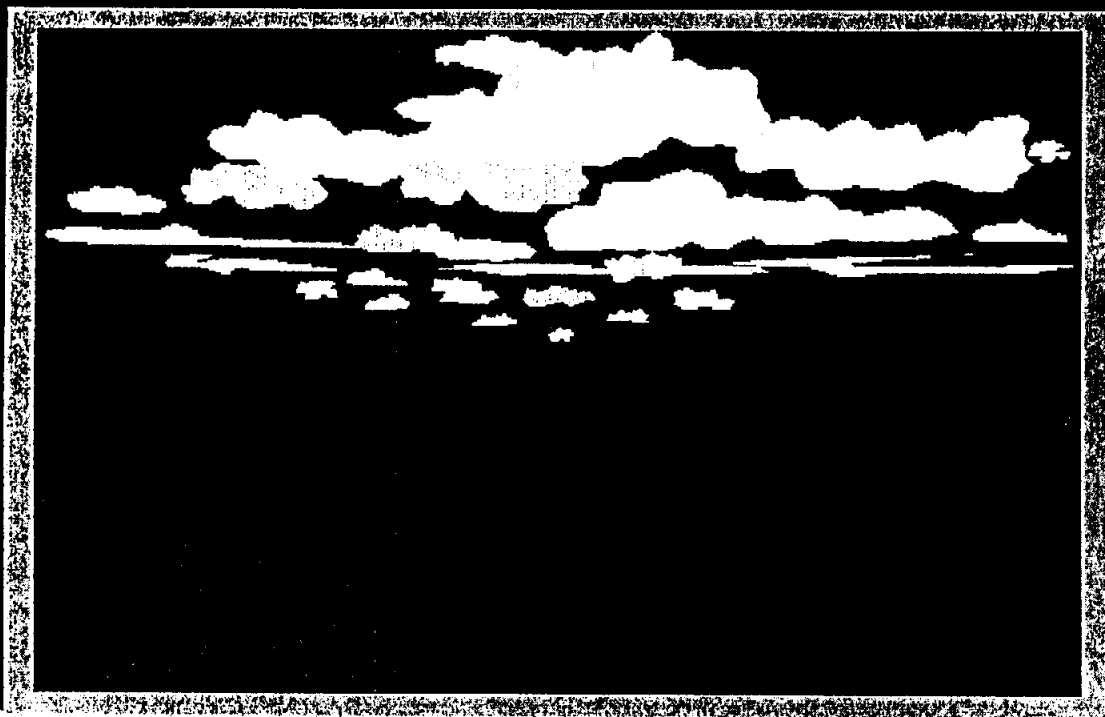


**FIGURE B-7**  
**WTI Crude Price vs FT Diesel Value**  
**(1993-1999)**



---

# **CLEAN DIESELS, CLEAN FUELS**



**EFI Conf.  
Jan 19, 1999**

**Tom Vachon,  
Caterpillar  
Inc**

---

# **THE CHANGING LANDSCAPE FROM A DIESEL ENGINE MFR'S PERSPECTIVE**

---

- EMISSIONS STDS. MORE STRINGENT
- GREENHOUSE GAS CONCERN
- DI & ELEC. CONTROL TO L.D.
- USER FRIENDLY & EURO. MARKET ACCEPT
- LT. TRUCK POPULARITY IN U.S.
- SMARTER ON EMISSIONS
- INDUSTRY/GOV. TEAMING



# CHANGES--->IMPACTS

---

EMIS. STDS. MORE STRINGENT--->DIESELS CLEANER

SMARTER ON EMISSIONS----->BETTER THAN IMAGE

CLIMATE CHANGE----->DIESEL IMPORTANCE

DIESEL ACCEPTANCE IN L.D.-----> USER FRIENDLY

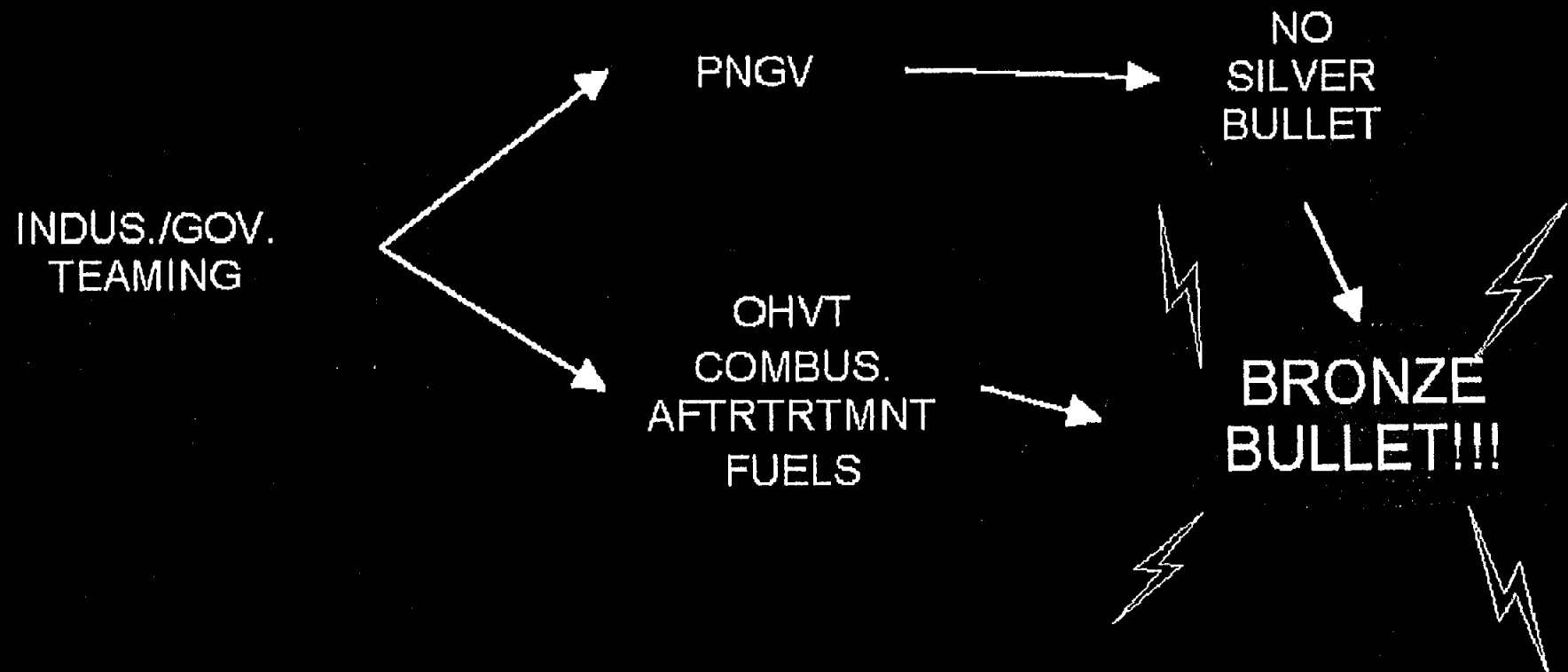
LT. TRUCK POPULARITY IN U.S.----->OPPORTUNITY

INDUSTRY/GOV. TEAMING----->SCI. LEVERAGE

# INDUSTRY/GOV. TEAMING---

## ----->RESULT

---



# THE BRONZE BULLET!

---

30 PPM MAX SULFUR FUEL

# **LOW SULFUR FUEL, ADDITIONAL BENEFITS**

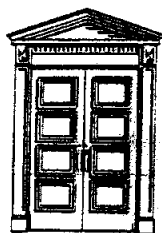
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- **LONGER USEFUL ENGINE LIFE**
- **REDUCED SULFATE PM**
- **REDUCED O&O COST**

# LOW SULFUR FUEL, ADDITIONAL BENEFITS

---

- 1.) Longer useful life; required to meet future emission stds.
- 2.) Reduced sulfate PM emissions
- 3.) Reduced O&O cost; required to sell new engines to realize their emissions benefit



Equity  
Research

Howard, Weil, Labouisse, Friedrichs  
Incorporated

December 18, 1998

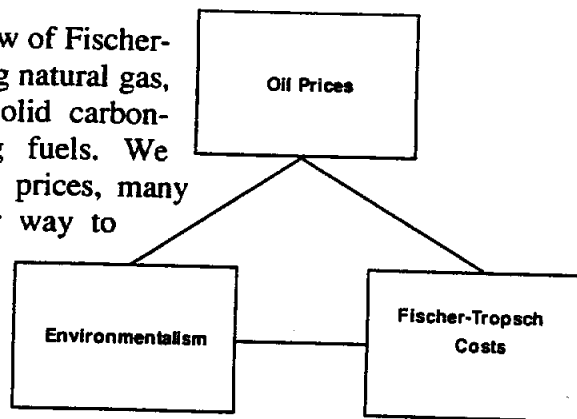
# FISCHER-TROPSCH TECHNOLOGY

Gas-to-Liquids, Solids-to-Liquids, Liquids-to-Liquids

**For Details Contact:** Arthur W. Tower III

## OVERVIEW

This report provides a comprehensive overview of Fischer-Tropsch technology "FT", a technology for converting natural gas, low-value refinery products, and coal and other solid carbon-bearing feedstocks into high-value, clean-burning fuels. We conclude in this report that despite current low oil prices, many Fischer-Tropsch projects are destined to find their way to market over the next few years. Further, the only "pure plays" in this new industry are Rentech, Inc. (RNTK) and Syntroleum Corporation (SYNM).



## HIGHLIGHTS

We believe the adoption of Fischer-Tropsch technology has the potential to profoundly affect the oil and gas business as well as the world we live in. Fischer-Tropsch technology has the potential to:

- Increase the use of cleaner sources of energy like natural gas.
- Unlock stranded gas resources.
- Unlock oil resources that would otherwise not be produced unless associated gas is produced.
- Increase the exploitation of heavy oil resources.
- Allow the continued use of "dirty" energy sources like coal and refinery bottoms in a more environmentally "friendly" way.
- Change the mix of uses energy sources are put to; for instance, making liquid transportation fuels from natural gas and coal.
- Reduce the costs to consumers of conventional refined products.
- Allow for population growth and increases in energy usage intensity which are inevitable while providing a means of economically reducing harmful emissions.

The extent to which the foregoing happens and the rate at which it happens will be a function of three factors as set forth in the schematic above and which are the principal focus of this report.

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## INTRODUCTION

Over the last 2 years, there has been a great deal of attention focused on a technology to turn natural gas or other carbon-bearing feedstocks into what are traditionally thought of as refinery products such as diesel fuel and petroleum waxes. While the technology for doing this (known as Fischer-Tropsch) has been around since the early 1920s, in our opinion, the recent interest stems from two core things: (1) high oil prices in 1996 and 1997 and (2) the efforts of a company called Syntroleum.

In a \$20 per barrel oil price world, "FT," as it is referred to, is probably economic in a number of settings<sup>1</sup>. Further, Tulsa-based Syntroleum Corporation has developed what it believes to be technological breakthroughs that may make FT economic in a far lower oil price environment and has been very successful in getting that message out as well as signing a host of licensing and other deals with major oil companies and engineering companies. Also, it should be noted that normally tight-lipped Exxon Corporation, which has been involved in FT research for some 20 years, has begun in the last 2 years to speak out in the investment community about its technology and plans<sup>2</sup>.

The purpose of this report is to explore in detail, Fischer-Tropsch technology, what it is and how it works, to review the various players and potential projects, and to try to come to some conclusions as to what FT may mean to the energy industry as well as the world in which we live.

To set the stage for this report and perhaps to whet the reader's appetite to charge ahead in this sometimes-technical area, we believe...

- FT technology will change the oil and gas industry more than 3-D seismic, horizontal drilling, or deepwater drilling;
- it will, by far, eclipse in impact the downstream technologies that led to liquefied natural gas (LNG); and
- FT will ultimately rank in importance with the invention of catalytic cracking by Exxon, which led to modern refining of crude oil as we know it.

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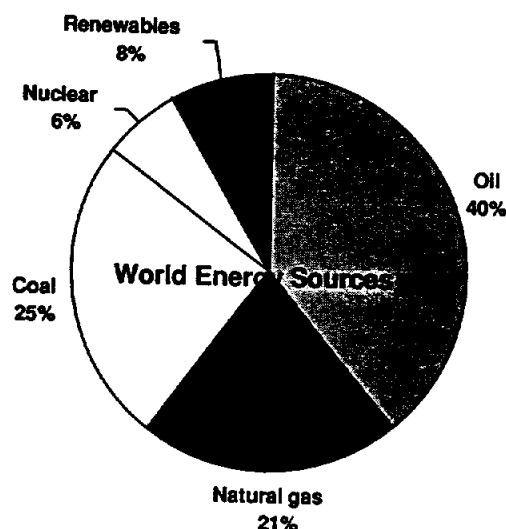
<sup>1</sup> It should be noted that the attention focused on Fischer-Tropsch technology has related mostly to the potential of converting natural gas to liquids and accordingly, most speakers and writers on the subject of Fischer-Tropsch technology use the term "gas-to-liquids" as the catch-all phrase to describe Fischer-Tropsch. We have avoided the use of this term as it may be misleading as we intend to cover all aspects of Fischer-Tropsch. FT can start with a gas, liquid, or solid and produce gas, liquids, and solids. Therefore, we have chosen to entitle this report "Fischer-Tropsch Technology" and use the term "Fischer-Tropsch" rather than "gas-to-liquids" as our "catch-all phrase."

<sup>2</sup> While Syntroleum has undeniably been the most vocal advocate of FT, a Wall Street Journal article October 30, 1996, which primarily discussed Exxon's GTL process, may well demarcate the beginning of the "race-to-market" for FT technologies. In that article, Exxon senior executives were quoted as essentially saying that they believe Exxon's FT technology had reached the commerciality stage. Moreover, Mark Agee, president of Syntroleum, acknowledges that "once Exxon said it could be done..." Syntroleum found it far easier to access the decision makers necessary to license its technology.



## WORLD ENERGY OVERVIEW

The starting point to understanding the potential for Fischer-Tropsch technology is to understand something about world energy sources and world energy uses. In broad terms, energy sources can be categorized as oil, coal, natural gas, nuclear, and "renewables" (solar, biomass, etc.). The chart below shows the relative mix of different sources of energy based upon recent United States Department of Energy (DOE) data.



Source: U.S. Department of Energy, *International Energy Outlook, 1998*.

As the chart shows, oil is currently the most consumed energy source, followed by coal and then natural gas.

As to energy use, the table below sets forth recent estimates.

World Energy End Use	Total	Oil	Coal	Gas
Transport	28%	55.1%	0.9%	3.6%
Industry	37%	20.0%	79.3%	43.5%
Other*	28%	18.6%	0.2%	52.9%
Non-energy	6%	6.3%	19.5%	0.0%
	100.0%	100.0%	99.9%	100.0%

\*Agricultural, residential, and non-industrial commercial uses.

Source: International Energy Agency. Data for 1995.

What is clear from this table is that the majority end-use of oil is for transport, coal is used mainly for industry, and natural gas is used for home, and non-industrial office, uses and agriculture<sup>3</sup>. Why isn't use equal? Why in many parts of the world is oil the preferred transport fuel, coal the preferred fuel to make electricity, and natural gas the preferred fuel for heating?

<sup>3</sup> For the remainder of this report, we are going to ignore discussions of solar and other renewable energy sources. While they will no doubt eventually become major, and perhaps dominant, energy sources, we believe the time frame is well beyond the next decade or two. Further, due to all of the problems with nuclear power, we are going to assume that its consumption will decline. (In fact, IEA forecasts a decline over the next 20 years.)

**A critical factor in understanding this report is recognizing and understanding that the uses energy sources are put to is directly related to the sum of extraction costs, transportation costs, the costs of converting an energy source to a usable form, and the costs of consuming that usable form. For example, oil is the dominant transportation fuel because it is cheapest to refine into gasoline and diesel and use in a car or bus. Moreover, pollution is part of the cost equation. What this report seeks to examine is the potential of Fischer-Tropsch technology to change this underlying cost structure.**

Whether or not the relative mix of energy sources will remain the same and whether or not the conversion of those sources to fuels used for transportation, industrial purposes, and non-industrial, non-transport uses will remain static will be determined by six variables:

- 1) Energy demand growth
- 2) Resource price
- 3) Resource extraction cost
- 4) Resource-to-product conversion cost
- 5) The cost of fuel consumption
- 6) Environmental concerns

While the first three variables are no doubt critical to the acceptance of FT technology, we would argue that as long as we experience modest increases in demand growth and prices and modest decreases in extraction costs, the last three variables are by far the more important.

We would argue that in a world whose population is inexorably growing, static energy demand or a decline in demand is rather difficult to envisage despite the current short-term reversal of recent years' growth trend. The International Energy Agency (IEA) forecasts that world energy use will grow by 54% from 1997 to 2015 (from 365 quadrillion btus<sup>4</sup> to 562 "quads") or about 3% per year. In that time period, it expects oil use to increase 50%, coal use to increase 37%, and natural gas use to increase 86%. Enron Corporation forecasts total world energy use to increase to 564 quads over the same time period and natural gas use to increase 91%.

Despite the current malaise in the Asia-Pacific region, the location of world gross domestic product is changing. In 1980, 78% was focused in North America, Western Europe, and Japan. In 1995, the figure was 75%, and by 2010, it is expected to be 70%. Further, while industrial countries use 75% of global fossil fuels (despite accounting for only 25% of the world's population) this mix is changing as well. Developing countries have been increasing, and will continue to increase, intensity of fuel usage and concomitantly, the absolute amount of fuel use.

Shell Oil, in a recent publication on Renewable Energy notes that from 1980 to 1990 world electricity demand increased 38% (from 8300 to 11500 terawatt hours per year<sup>5</sup>). Shell further goes on to say: "The greatest increase was in the developing countries where the annual increase in demand was three times that of developed countries. The World Bank estimates that some 600,000 MWe [megawatts] of new electricity generating capacity will be needed by the end of the 1990s, more than half of which will be

---

<sup>4</sup> A "btu" is a "British Thermal Unit" and is a measure of energy. Specifically, the amount of energy represented by a btu is the amount of energy it takes to raise the temperature of a pound of water by one degree Fahrenheit. To put these figures into context, 365 quadrillion btus is equal to around 68 billion barrels of oil. Current oil consumption in the world is around 27.4 billion barrels per year or about 75 million barrels per day. (The btu to oil conversion is based upon IEA conversion factors.)

<sup>5</sup> To put that number into context, 11500 terawatt hours of electricity use per year equals approximately 20 million barrels of oil use per day (based upon IEA conversion factors).

required by the developing countries, India and China in particular." (It should be noted that electricity is made from a number of energy sources. Per the IEA, those sources currently are: *coal* - 37%, *hydro* - 19%, *nuclear* - 18%, *natural gas* - 15%, *oil* - 10%, and *other* - 1%).

In short, energy demand will increase and developing country demand will become a greater component of world demand.

As to **price**, while it certainly is a variable, we believe it **will affect the timing of change**, not whether change occurs. See Appendix I for a discussion of our views on the current and near-term future price of crude oil. With regard to the longer-term, while some advocate apocalyptic scenarios of energy resource scarcity and runaway prices, we are in the camp that believes that the world has abundant stores of energy which will continue to be extracted in a timely manner to meet demand. Human ingenuity is ultimately the key resource and there is no shortage of that.

With regard to **extraction costs**, we believe they **will continue to decline modestly** each year as they have throughout the years and assume that there will be no quantum breakthroughs in extraction costs which will vault coal or oil or natural gas into a substantially better competitive position.

If we accept the foregoing arguments about energy demand, prices, and extraction costs, it is the cost of converting energy sources to energy products, the cost of using those products, and environmental issues which will ultimately affect the acceptance of Fischer-Tropsch technology.

We hope this report will make clear that the "cost" of products made with Fischer-Tropsch technology can, in certain applications, be competitive now with conventional energy products and therefore, the selling price can be competitive as well. Moreover, as we will show, one of the fundamental attractions of Fischer-Tropsch products is that they can be consumed in exactly the same way that conventional energy products are consumed (and at the same cost—or a lesser cost if one factors in the cost of pollution). There is no need for exotic new engines or equipment.

With regard to environmental factors, we would point out that to some extent, the IEA demand growth forecasts mentioned earlier, mirror the relative pollution problems created by coal, oil, and natural gas which is another way of saying that even in a world of modest demand growth, or no demand growth, due to concerns about the environment, cleaner fuels will garner greater market share. That is the topic of the next section of this report.

## ENVIRONMENTAL ISSUES

Using energy pollutes. Everyone knows that. But how much? The table that follows puts energy pollution expressed in terms of carbon emissions<sup>6</sup> into a relative context.

World Energy Usage & Emissions	Energy Carbon Emissions		
	Usage	%	Amount*
Oil	39%	43%	2562
Natural gas	21%	18%	1095
Coal	25%	39%	2317
Total†	85%	100%	5974

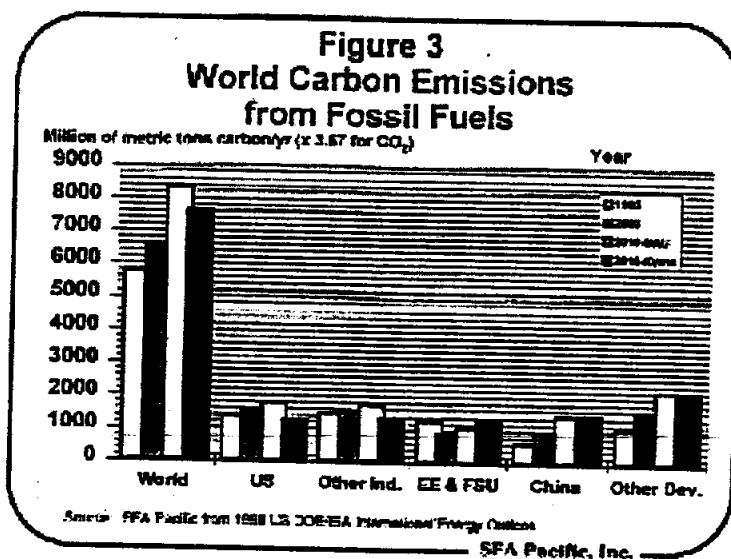
\*Millions of metric tons

†Energy usage does not add to 100% as we have left out nuclear and renewables.

Source: US Department of Energy, International Energy Outlook, 1998.

As this table indicates, while oil is currently the polluting "king" in absolute terms, coal is the dirtiest fuel and natural gas the cleanest. It does not take a rocket scientist to figure out that world energy policies should favor natural gas over its two competitors and that coal usage should increasingly come under pressure unless some cleaner means of using it can be found.

But are environmental concerns a real factor driving energy sources and uses? First, haven't we gotten better over the years? The answer is yes and no. Carbon emissions per unit of energy used have declined, but absolute levels are still increasing as the chart that follows indicates.



<sup>6</sup> In this section, we will focus exclusively on pollution in the context of carbon emissions—so called "global warming"—and ignore all of the other pollutants such as nitrogen oxide and sulfur dioxide ("NO<sub>x</sub>" and "SO<sub>x</sub>"). Further, throughout this report, while we talk about forms of pollution other than carbon, they are not treated in as great detail as carbon is in this section. This decision was made not as a judgment about the relative problems and challenges created by carbon versus other pollutants but rather for expediency as a comprehensive discussion of all material forms of pollution pertinent to Fischer-Tropsch technology would result in this already extensive report ballooning to an even more unacceptable size. Rather, we have chosen to discuss carbon emissions in depth as a proxy for all important forms of pollution. In a later report, we may more fully explore the different types of pollution the world is faced with and how Fischer-Tropsch technology can specifically address these.

With regard to the United States, the U.S. Energy Information Administration reported that carbon emissions in the U.S. in the 1990 to 1997 period were up 10%; 1.4% in 1997 alone.

The state of "world" thinking about environmental issues can perhaps best be summarized by reviewing the carbon emissions reduction targets set in December 1997, in Kyoto, Japan, by more than 150 countries—the so-called "Kyoto Protocol."

**Most developed nations must decrease carbon emissions by 6%-8% below 1990 levels by 2010.**

The Protocol does not set emissions reduction targets for developing nations and has certain other provisions which are highly controversial but we will ignore these as they are not all that germane to the main focus of this report. What is germane is that, if fully and strictly implemented, the Kyoto Protocol could wreak havoc.

The U.S. target emissions level by 2010 is 1,281 million metric tons (mmt) of carbon. The target reduction for the U.S. is 566 mmt. This reduction represents a 31% decrease from the U.S. government's "business-as-usual" forecast of 1,847 mmt in the year 2010.

The European Union target under the Kyoto Protocol is a 163 mmt reduction from 1990 levels or 16% less than the EU's business-as-usual 2010 forecast of 1,001 mmt of carbon emissions.

In short, to meet the Kyoto Protocol targets, "something" has to change, and change radically. There are four factors that can change carbon emissions from fossil fuels as identified by the American Petroleum Institute<sup>7</sup>.

- *Population,*
- *Per capita GDP,*
- *Energy intensity (amount of energy use per person),*
- *Carbon content of energy used.*

One or more of these must decline in order for emissions to decline. If we assume that only energy intensity changes, the U.S. would have to use 4.5% less energy per year between now and the year 2010 to meet its Kyoto Protocol emissions reduction target. This is two times the decline that occurred during the 1974-1986 "energy crisis" period and five times the rate of decline that is forecast by the U.S. Department of Energy between now and the year 2010. Further, it should be noted that during the energy crisis, real fossil fuel prices (adjusted for inflation) **quadrupled** and this obviously provoked the contraction in U.S. fuel use<sup>8</sup>. So, the target for the U.S. is probably unworkable and it is unlikely to be fully realized, however, one thing the Kyoto Protocol makes clear, the momentum for reducing carbon emissions is great and the will to effect real change is increasing.

While we can criticize the science underpinning global warming, we should heed the words of Dale Simbeck of SFA Pacific, Inc., engineering and economic consultants, as delivered in a paper at the October 1998 Gasification Technologies Conference:

<sup>7</sup> In a study entitled "Implications of the Kyoto Protocol Targets for OECD Countries" issued May 1998.

<sup>8</sup> Per Oil & Gas Journal Energy Statistics Sourcebook, 13<sup>th</sup> Edition, 1973 U.S. demand for all oil products was 17,308 thousand barrels per day. The corresponding figure for 1985 was 15,726 tbd.

...whether or not there is conclusive evidence of global climate change has become irrelevant. This is because global climate change has become a political issue wherein perceptions can become reality and positions reflect vested interests.

In summary, we suspect that the final effect of the Kyoto Protocol will be carbon emissions at a level somewhere below that which would result from "business-as-usual" and somewhere above that set forth in the Protocol.

Finally, we would like to make one last observation with respect to environmental issues and this observation relates to the issue of energy prices as discussed in the previous section of this report. High energy prices are an antidote to the pollution problem as they damp demand and thus emissions. But the flip side of that equation is that high prices spur the adoption of alternative technologies which are less polluting (like Fischer-Tropsch technology as we will see in the remainder of this report). On the other hand, low energy prices, such as we are experiencing now, increase energy consumption and hence, emissions, which leads to increasing political pressure to reduce those emissions.

**The bottom line is that as long as there is the political will to reduce harmful emissions, emissions-reducing alternate technologies will find their way into the marketplace regardless of whether energy prices are high—or low.**

## FISCHER-TROPSCH TECHNOLOGY

### CHEMISTRY

What is "Fischer-Tropsch" technology? Simply stated, it is a process that rearranges carbon (and hydrogen<sup>9</sup>) molecules. Without giving a chemistry lesson, it is important to understand something about the chemical make up of hydrocarbons in order to have a basic understanding of Fischer-Tropsch. It should come as no surprise that "hydrocarbons"—crude oil and natural gas—contain carbon (and hydrogen) and simply stated, the number of carbon atoms in each molecule determines whether or not, at room temperature, the hydrocarbon is generally in a gaseous state—natural gas—or in a liquid state—crude oil<sup>10</sup>. Generally, at room temperature, if there are 1 to 4 carbon atoms per molecule ( $C_1$  to  $C_4$ ), the hydrocarbon is gaseous—natural gas; if there are more carbon atoms than 4, the hydrocarbon exists in a liquid state—oil; and above 20 carbon atoms per molecule, typically the hydrocarbon exists in a solid state.

To be completely accurate, both oil, and to a much lesser extent, natural gas, have lots of other "things in them"; sulfur, heavy metals, etc. Moreover, crude oil is not a liquid with a uniform number of carbon molecules. In other words, oil is not just say  $C_6$  or  $C_{10}$ . It is a gumbo or jumble of various molecules with different numbers of carbon (and other) atoms<sup>11</sup>.

When one refines crude oil, what one is doing is breaking up that jumble of molecules. Of course, one must extract the "bad stuff"; the sulfur and heavy metals, but after that, the process basically consists of separating the molecules into homogeneous batches. You can think of it as a kind of collating process where

<sup>9</sup> While hydrocarbons generally consist of both carbon and hydrogen atoms, the short-hand for referring to hydrocarbons is to refer to just the number of carbon atoms (C) so we will adopt that approach herein as well.

<sup>10</sup> Like many of the technical descriptions in this report, this explanation is somewhat of an oversimplification for it is not only the number of carbon atoms but, the arrangement of those, and other atoms in the hydrocarbon molecule that determine if the hydrocarbon exists in a gaseous, liquid, or solid state.

<sup>11</sup> Likewise, natural gas contains several distinct and different gases with distinct chemical structures such as: methane ( $CH_4$ ), ethane ( $C_2H_6$ ), and propane ( $C_3H_8$ ). Further, natural gas often contains sulfur, trace amounts of metals and even a light form of crude oil referred to as condensate.

one puts all of the  $C_5$  molecules together, all of the  $C_{10}$ s, etc. That "batching" process produces petroleum products such as naphtha and diesel. (In fact, the batches are not limited to single categories of carbon content, but rather, a range. Typically, naphtha is  $C_5$  through  $C_9$ , Diesel is  $C_{10}$  through  $C_{20}$ . These ranges are also called "fractions" or "cuts.")

The batching is accomplished through a variety of means, the simplest of which is the application of heat, as many of the different fractions will separate at different temperatures. (It should also be noted that often, natural gas is in effect commingled with crude oil—so-called "solution gas"—and must be separated out from the oil before the oil is further refined.<sup>12</sup> It should also be noted that this simplest form of heating crude oil in order to cause the fractions to separate is called "distilling" and the fractions or cuts are sometimes referred to as "distillates.")

It is interesting to note that in the early days of the oil industry, simple distilling was the only known refining technique and refiners used it to "get at" the kerosene fraction in the oil which was used to replace whale oil in lamps. The remainder (of the fractions), they just threw away, often by burying the material. In a way, that old story encapsulates the entire technological history of the refining industry. Refiners have been on a quest, from day one, to improve technology so that they can use more and more of each barrel of oil—and throw away or sell for low prices, less and less. As we shall see later in this report, one important application of Fischer-Tropsch is nothing more than a continuation of that quest.

At this point it may also be helpful to introduce some nomenclature we will be using throughout the remainder of this report. Refiners often refer to the refined fractions as "light" or "heavy." The light fractions have less carbon atoms per molecules and are literally lighter in weight by volume such as naphtha from which gasoline is made.

Diesel is often referred to as a "middle distillate" because its number of carbons is in the middle range relative to the overall type of fractions produced in the refining process. It is also important to point out that in the "collating" or "batching" process we referred to earlier, in some cases, the fractions or cuts are viable, usable end products with no requirement for further processing or upgrading (as in the case of diesel fuel) but, most fractions do require further refining and processing steps to get to the end product (like gasoline).

Refiners also think in terms of a barrel of oil going into a refinery and a barrel of products coming out and use the terms "heavy" and "light" to refer to the parts of the barrel coming out. Therefore, you will hear the expression "heavy end of the barrel" used to refer to the products with a higher number of carbon atoms—so-called "long-chain" carbon atoms. The heavier products are also referred to as "residual" or "resid." The heaviest part of the barrel is also referred to as the "bottom of the barrel" or simply, "bottoms." (To see a breakdown of all of the products that can come from a "typical" barrel of oil, see Appendix II).

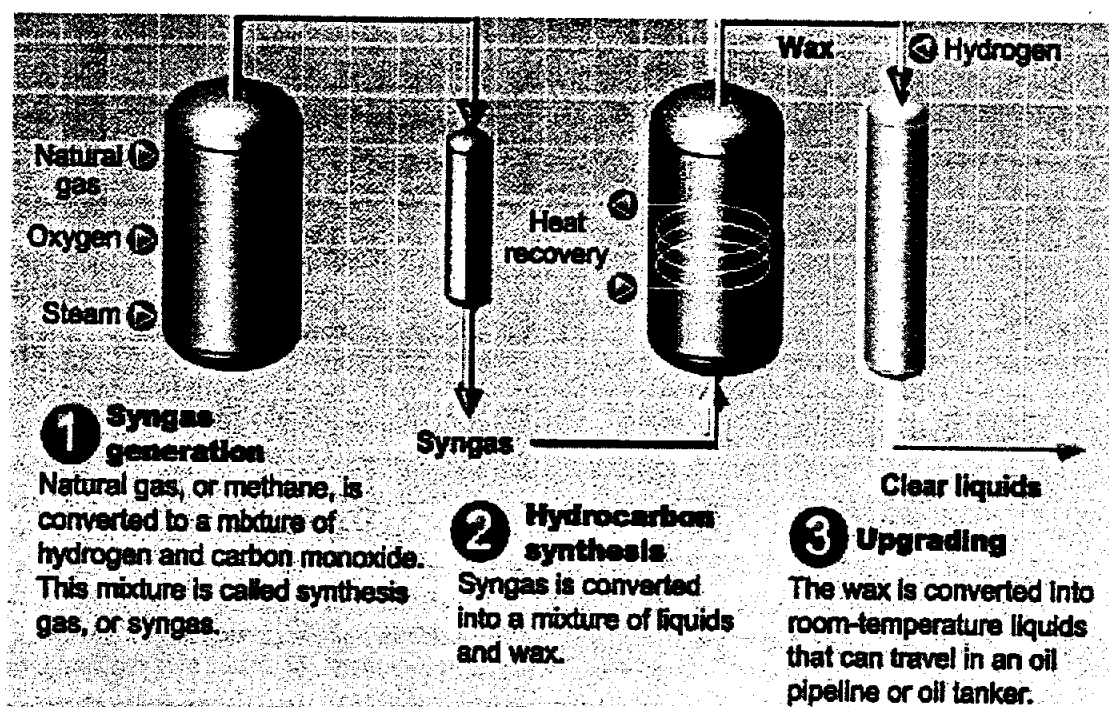
After trudging through this explanation, it should not be hard to imagine that some creative scientists would come to the conclusion that since natural gas contains the same carbon and hydrogen atoms that are the basic building blocks of all of the products made from oil it should be possible to make these products from natural gas as well. Further, why limit oneself to natural gas. Anything containing carbon would seem to be a candidate for conversion into the products we normally associate with crude oil refining. (Coal obviously contains carbon and in fact it was the focus of much of the pioneering work done in this area as we will discuss in the "History of Fischer-Tropsch" section of this report). At this point we are ready to move onto the description of the Fischer-Tropsch process.

<sup>12</sup> At this point you may be confused as we have said that natural gas can contain oil and we call that oil "condensate" and we have said that oil can contain natural gas and we call that natural gas "solution gas." What gives? The answer is the natural state of things is far more complex than we can describe in simple terms. But, both of our statements are accurate. The high pressure stream of natural gas that comes flowing out of a well into a gathering system may contain some condensate and that condensate will get separated out merely by allowing the gas to stand still for a period of time (though more robust approaches are often used). Likewise, some amount of natural gas is found in most oil.

## PROCESS

The first step in the FT process is separating the constituent parts of natural gas (or, as mentioned, coal, or any other carbon bearing or "carbonaceous" feedstocks). These constituent parts are carbon, as previously described, and hydrogen, as previously mentioned. Separation may be accomplished in several different ways, which we will describe in greater detail later (including the various *pros* and *cons* of different approaches). This separation goes under several names including "reforming" or "gasification"<sup>13</sup>.

Whatever approach is used, the first step in the process separates or breaks apart the bonded carbon and hydrogen molecules of natural gas (i.e.,  $\text{CH}_4$ ) into two separate molecules—hydrogen ( $\text{H}_2$ ) and carbon monoxide ( $\text{CO}$ ). (The ratio of hydrogen to carbon monoxide is a critical factor in the FT process and while not important here, we will have a lot to say about it later in this report). This mixture of  $\text{H}_2$  and  $\text{CO}$  is called "synthesis gas" or simply "syngas."



Source: Exxon Lamp Magazine Summer 1998

Without getting into balancing chemical equations, in order to make syngas, we have to add something else into the mix in the syngas generation stage and that something else is oxygen which should make sense because if we start with carbon ( $\text{C}$ ) and hydrogen ( $\text{H}_2$ ) and we want to end up with  $\text{H}_2$  and  $\text{CO}$ , we have to add "O" (the oxygen molecule).

It should be noted that the introduction of oxygen into the process of making syngas is a critical step and a very expensive step. In fact, according to various studies, the cost generally accounts for some 20-30% or so of the combined capital cost of the three steps depicted in the schematic on the previous page. Further, there are several different ways to introduce oxygen into the process—from air, from water (in the form of steam), from  $\text{CO}_2$ , or from a combination of one or more of these sources. (It should be noted that Syntroleum, a leading FT technology company, introduces air directly into its syngas step as its oxygen source<sup>14</sup>). Later in this report, we will have a lot more to say about this introduction of oxygen in some form.

<sup>13</sup> It should be noted that the gasification or reforming step used to produce syngas is not unique to Fischer-Tropsch. It is employed in a number of settings in industry to produce power, steam, and various chemicals and intermediaries.

<sup>14</sup> By volume, air is about 21% oxygen, 78% nitrogen, and 1%, other.



It should also be noted that the generation of syngas is not **part** of the Fischer-Tropsch process, but is **essential** to it. Moreover, given the complexity of the syngas step, the many different approaches available, and the high cost, FT technology companies are very focused on this step and generally have their own proprietary, and in some cases, patented, designs. Therefore, when we talk about FT technology, the syngas step is usually considered part of the overall technology.

The Fischer-Tropsch process starts when we introduce the syngas into a reactor that contains a catalyst<sup>15</sup>. The design of the reactor and the type of catalyst are critical to the efficacy of the overall process and again, we will cover both of these topics in depth later in this report but at this point it is important to know that two basic types of catalysts are used in Fischer-Tropsch reactors, cobalt or iron<sup>16</sup>. Once in the reactor, the catalyst accelerates the reaction of the syngas and the H<sub>2</sub> and CO gases are generally chemically altered into longer chain carbon molecules; generally longer than the C<sub>1</sub> to C<sub>4</sub> range described in the previous section. Some of these longer-chain molecules form petroleum waxes and some become middle distillate liquids (from here on in this report, we may refer from time to time to these products as "FT products" or as "synfuels"). The third and final stage in the process is to upgrade the synfuels to the exact specifications for end use<sup>17</sup>.

In addition to the wax and middle distillates that come out of this process, water (H<sub>2</sub>O), some alcohols, and carbon dioxide (CO<sub>2</sub>) are produced in the FT process and these have to be disposed of or used. Further, a lot of heat is used and/or given off in the FT process and how it is handled is critical. We will discuss both of these issues later in this report.

So that's Fischer-Tropsch in a nutshell, but who are Fischer and Tropsch? How did FT first get developed and what has been its history? That is the focus of the next section of this report.

## FISCHER-TROPSCH HISTORY

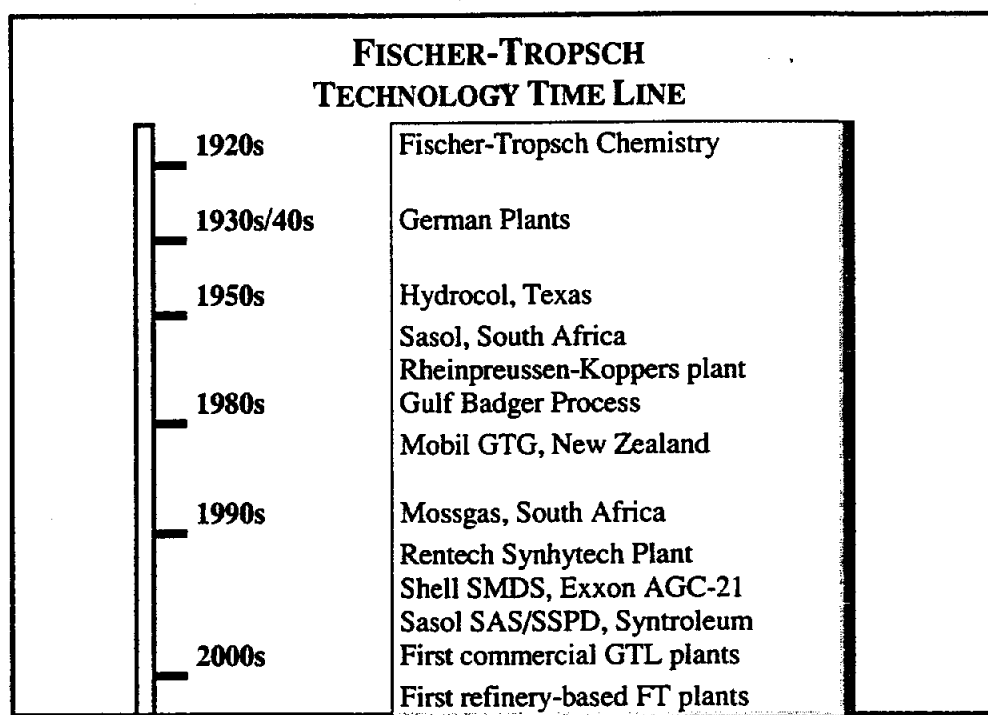
As Einstein is the "Father of Relativity" and, if we can be fractious, James Brown is the "Godfather of Soul," FT is the progeny of Hans and Franz (Tropsch and Fischer, respectively, that is). In 1923, these two German scientists, working at the Kaiser Wilhelm Institute für Kohlenforschung, discovered the chemical reaction behind the process and later, effected the first conversion of synthesis gas into synfuels. FT was then subsequently employed by various German companies in full scale industrial plants to manufacture synfuels, principally motor diesel, for use by the German "War Machine" during WW II. Germany's sources of crude were limited but its coal reserves were substantial. Thus it became critical that it find a means to obtain fuel for tanks, planes, and motor vehicles and FT was the solution. While the fuel was not by any means commercial (i.e., cost competitive with traditional fuels), it was usable and the Germans peaked their production in 1944 at 16,000 barrels per day. In all, during the war years, it is estimated that some 4,500,000 barrels of synfuels was made during each of the war years. The time line that follows is a good snapshot of the developmental history of FT.

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<sup>15</sup> A "catalyst" is a substance that facilitates or accelerates a chemical reaction without itself being consumed by that reaction.

<sup>16</sup> In reality, there are other catalyst materials that can be used. Moreover, "cobalt" and "iron" catalysts are really shorthand descriptions of the actual composite materials used as catalysts in Fischer-Tropsch reactions. However, for purposes of this report, we will ignore these complications as they are not essential to understanding the basic processes we are describing or the strategic implications of FT as described herein.

<sup>17</sup> It should be noted that in some cases, no upgrade may be necessary. For instance, some end-products may be used as feedstocks to make other products and FT diesel may be directly usable with no further upgrading.



The Hydrocol plant in Texas was a fascinating experiment and period in the history of FT and represented the confluence of several events. Germany was not the only country working on technologies to make synthetic fuels. The U.S. and UK were also in the game. In 1944, the U.S. passed a Synthetic Fuels Act that charged the Bureau of Mines (BOM) with the responsibility to develop synthetic fuels. When the Allies won WWII, both the U.S. and UK in effect "deposed" the German scientists working in the FT area. In fact, after the war, H. Pichler, one of Fischer's lead scientists before and during WWII went to work for the U.S. BOM.

The U.S. BOM actually dismantled two German plants and brought them back to the United States. They were brought to Louisiana, Missouri. One of the two plants actually was assembled and produced around 100 barrels per day of FT products for several years.

In addition to the German plant in Louisiana, Missouri, the Bureau of Mines had another plant built—this time from scratch—in Brownsville, Texas. A company called Hydrocarbon Research Inc. developed an FT process based on the German work for use in this plant. Called the "Hydrocol" plant, it began operations in 1950 using natural gas as a feedstock. The plan was to make gasoline, but the plant had start-up difficulties followed by redesign only then to run into an escalating cost for natural gas and declining oil prices which changed the economic climate and led to the plant's abandonment. Texaco was a partner in the Hydrocol plant and subsequently bought all of it but never reopened the plant.

Speaking of Texaco, they were one of the earliest researchers in the FT area and that legacy still exists in many respects. However, today, Texaco does not have its own in-house developed FT technology to use or license to others,<sup>18</sup> but Texaco is the leading licensor of the first stage in the overall FT process—"gasification"—with over 100 projects operating worldwide gasifying such diverse feedstocks as coal, coke, natural gas, etc. Texaco's "gasification" business dates back 50 years to the company's early involvement in Fischer-Tropsch research. In 1947, Texaco built its first FT pilot plant in Montebello, California—a 120-

<sup>18</sup> But Texaco has made up for the lack of an "organically" grown technology by licensing FT technology from both Rentech and Syntroleum as will be discussed later in this report.

barrel per day plant. Work on this plant was abandoned for the same basic reasons the Hydrocol plant was abandoned—low oil prices in the early 1950s. However, the syngas reactor for this project was in effect the pilot plant for Texaco's gasification technology.

In the late 1940s, the next substantive deployment of FT technology was germinating. The South African Government, through the predecessor company to the South African Coal, Oil, and Gas Corporation ("Sasol"), began FT research. The first of three plants, Sasol I, was brought onstream in 1955. Interestingly, its initial technology came from the Hydrocol plant. Two additional units, Sasol II and Sasol III were streamered in the 1980s. All three of these plants use coal as a feedstock. Sasol's main goal was to make gasoline from coal as South Africa has a lot of coal and little oil and obviously, at the time these plants were built, was the subject of an international boycott and unable to import gasoline. Today, all three Sasol plants are operating as well as a plant called "Moss gas" in South Africa, which licenses the Sasol FT technology and converts natural gas to FT products. These plants are currently producing around 160 thousand barrels per day of FT products.

In the early 1950s, the first commercial-scale **slurry** reactor using an iron-based catalyst was operated. Designed by Drs. Kolbel and Ackermann, the Rheinpreussen-Koppers plant in Homberg-Niederhein, Germany operated using syngas made from coal.

The next thread in the FT story starts in Pittsburgh, Pennsylvania. In the late 1970s with oil prices once again on the rise, another synthetic fuels act was passed in the United States. Gulf Oil teamed up with a company called Badger Engineering (now owned by Raytheon). Badger had been involved with Sasol early in Sasol's development of FT (using iron-based catalysts). Gulf/Badger began work on cobalt catalysts. In 1979 they started up a 35-barrel per day pilot plant which ran for several years. Then, Chevron bought Gulf and oil prices dove again leading to the closing of the FT R&D effort. Ultimately, Chevron sold its Gulf/Badger Fischer-Tropsch R&D to the Royal Dutch/Shell Group.

While Gulf was progressing its R&D effort; Exxon was on a similar path. After the Arab oil embargo of 1973, Exxon geared up a grassroots research and development effort at its R&D center in New Jersey. Exxon calls its proprietary gas-to-liquids ("GTL") technology "AGC-21" which stands for "Advanced Gas Conversion for the 21st Century."<sup>19</sup> Exxon has spent some \$300 million on Fischer-Tropsch R&D. Exxon holds around 1,500 patents worldwide on Fischer-Tropsch-related technology and processes. Construction of a 200-barrel per day pilot plant was begun at the company's massive 400,000+ barrel per day refinery in Baton Rouge, Louisiana in 1989. For 3 years, until 1992, Exxon successfully demonstrated its technology. Recently, Exxon has been studying FT plants in some one-half dozen locations around the world including Qatar and Alaska, among others.

In 1980, Mobil Corporation began its FT R&D effort building a small pilot plant utilizing iron-based catalysts. Studies conducted in 1983 indicated to Mobil that the process was not economic and the company stopped development, but interestingly, Mobil did build a commercial-sized 14.5-thousand barrel per day unit in Montuni, New Zealand to convert natural gas to methanol and methanol to gasoline based on, in part, some of the FT R&D though the process was not FT. This project was technically successful, but an economic failure and subsequently, the plant was sold and turned into a methanol only facility.

In the 1980s, several other companies were also involved in Fischer-Tropsch research including Air Products which first worked on cobalt processes and then in 1992, switched to tests of conventional iron catalysts. Statoil also pursued research into cobalt-based FT processes building several laboratory and pilot scale reactors.

<sup>19</sup> As we noted at the beginning of the report, we prefer the term "Fischer-Tropsch technology" to "gas-to-liquids". However, in this case, the term "gas-to-liquids" is appropriate and accurate as Exxon's AGC-21 technology is truly a technology to convert natural gas to middle distillate liquids (and wax). Therefore, when "gas-to-liquids" or "GTLs" are applicable, we will use these terms.

The Royal Dutch/Shell Group ("Shell") FT technology is called "SMDS" which stands for "Shell Middle Distillate Synthesis." Shell commenced development of this technology in 1973 at the Shell Research Center in Amsterdam substantially completing the work by 1990. Investment to date has been \$1 billion to \$1.5 billion. In 1989, Shell announced plans to build a 12,500-barrel per day plant to convert natural gas to FT products. At a capital cost of around \$850 million, the plant went into commercial operation in 1993. Shell's plant processed around 100 million cubic feet per day of natural gas using a cobalt-based catalyst. Unfortunately, the oxygen unit in Shell's plant exploded in December of 1997. Shell has announced plans to rebuild.

Another potentially significant player in the FT field was also developing its technology in the 1980s—not a major oil company, but a small Colorado-based group whose technological ideas grew out of catalyst research done at the U.S. Government's China Lake missile research lab and conversion of biomass to fuel at the United States' Solar Energy Research Institute ("SERI"). Dr. Charles (Chuck) Benham, was the scientist that had worked at both of these places and in 1981, with business partners, he formed Rentech, Inc.

Rentech built its first pilot plant in 1982 using an iron-based catalyst. In 1992, the company's first commercial plant went into operation. Interestingly, Dr. Kolbel, who was instrumental in the Rheinpreussen-Koppers FT plant mentioned earlier and long considered the pioneer in the development of iron-based FT slurry reactor technology, was a consultant to Rentech in the design of this plant.

The "Synhytech" plant had a capacity of 235 barrels of FT products per day and was designed to use landfill gas. The project was funded by Fuelco, a subsidiary of Public Service Company of Colorado. Unfortunately, the landfill did not produce sufficient gas to meet the reactor specifications. The plant was successfully tested using purchased natural gas but the plant was uneconomical and was shut down.

In 1994, Rentech signed a licensing agreement with Indian company Donyi Polo Petrochemicals, Ltd. pursuant to which Donyi purchased the "Pueblo" plant and moved it to Arunachal Pradesh, India. The plan is for the plant to use flared natural gas as feedstock to produce approximately 300 barrels per day of FT products, primarily high value petroleum waxes. Plant start-up is scheduled for the end of the year 2000.

In October of 1998, Rentech signed an agreement licensing its FT technology to Texaco, Inc. Currently, Rentech holds nine patents relating to Fischer-Tropsch including several key patents and patent applications that relate to processes for enhancing the overall yield of FT products.

In 1984, another small company, Syntroleum was founded to commercialize its Fischer-Tropsch technology based on the work of Mr. Ken Agee. Mr. Agee's interest in the potential of Fischer-Tropsch dates back to his days as a natural gas plant engineer at Transoak Corporation in the early 1980s. Mr. Agee saw the need for a small mobile unit to convert natural gas that was not accessible to pipelines to a liquid form for transportation.

Syntroleum's process is based on cobalt catalysts and features a unique method for making synthesis gas (which is the first step in the Fischer-Tropsch process and is the subject of the next section of this report). Syntroleum has been highly successful in licensing its technology to a number of companies including Texaco, Inc., Atlantic-Richfield Company (ARCO), Enron Corporation, Marathon Group, YPF, and Kerr-McGee. Moreover, Syntroleum continues to actively pursue additional licensing agreements.

With Texaco, Syntroleum is planning to build a 2,500-barrel per day plant, which if successful, could lead to hundreds of plants possibly deployed offshore. With ARCO, Syntroleum has built, and is currently installing, a 70-barrel per day pilot plant at ARCO's Bellingham, Washington refinery. This plant will be used to test a new slurry reactor design.

Syntroleum also is in the planning stages to build an 8,000-barrel per day specialty products plant with partner Enron in Sweetwater, Wyoming. Syntroleum has licensed Lyondell Petroleum's lube oil technology, which will be used in the Sweetwater plant. Finally, Syntroleum recently signed (October 1998) an agreement to pursue research on FT fuels with Chrysler Corp.

## SYNTHESIS GAS MANUFACTURE

The technology for making synthesis gas is not new. Since the early 1920s, synthesis gas been made and then converted into methanol. Synthesis gas is also used to make ammonia, hydrogen, electricity, and steam.

Synthesis gas is created by one of two general methods, partial oxidation or reforming. Partial oxidation or "POX" is the older of the two processes. Now what do we mean by "oxidation"? Webster's Dictionary says to "oxidize" is "to combine with oxygen." For instance, when we light the gas coming out of our (gas) stove we are "oxidizing" that gas. The gas (which is primarily methane or  $\text{CH}_4$ ) burns in the presence of the oxygen ( $\text{O}_2$ ) in air. The resulting "products" are carbon dioxide ( $\text{CO}_2$ ) and a small amount of water ( $\text{H}_2\text{O}$ ). (The water comes off as a non visible vapor). The natural gas is completely "oxidized," that is, used up in this chemical process.

"Partial" oxidation refers to the fact that we limit the amount of oxygen that is allowed to react with the natural gas (or other carbonaceous feedstock) in the syngas reactor. The amount of oxygen has to be controlled because the objective is to convert the feedstock to hydrogen and carbon monoxide and if we put too much oxygen into the process we get a preponderance of carbon dioxide ( $\text{CO}_2$ ) instead of a preponderance of carbon monoxide ( $\text{CO}$ ).

In the reforming approach, oxygen is introduced into the syngas step principally through steam (Steam obviously is water in the vapor stage and water is  $\text{H}_2\text{O}$  and the "O" is what we are after in the steam. This approach is called "steam reforming" or more specifically, "steam methane reforming.") The steam and feedstock are pumped through tubes filled with a commercially available nickel catalyst. These tubes are inside the shell of the reactor vessel. The mix of solid catalyst, natural gas, and steam is kept heated to a level of around 1600 degrees Fahrenheit by a series of burners outside the tubes, in the firebox of the reactor's furnace. These burners are fired by natural gas or some other fuel source.

In their "pure" form, the fundamental distinctions between reforming and POX is that "classical" POX does not use a catalyst to create syngas whereas steam reforming does. In fact, as we discuss later, "modern" POX applications typically do use catalysts. These two processes produce the following end-product slate:

### TYPICAL SYNTHESIS GAS COMPOSITION

(Percent yield based upon methane feed)

	$\text{H}_2$	$\text{CO}$	$\text{CO}_2$	Total
Steam reforming	75	15	10	100
Partial oxidation	50	45	5	100

Source: Petrochemicals in Non-Technical Language

As the table shows, undesirable  $\text{CO}_2$  is produced in both approaches, though less in the POX case. Also, the initial  $\text{H}_2$  to  $\text{CO}$  ratio in steam reforming is 5:1 and in POX, about 1.1:1. These relationships have to be adjusted to produce the correct syngas ratio for Fischer-Tropsch. In steam reforming, in order to adjust this ratio to the desired 2:1,  $\text{CO}_2$  must be recycled. In partial oxidation, steam or water must be added to increase the  $\text{H}_2$ : $\text{CO}$  ratio to 2:1<sup>20</sup>.

<sup>20</sup> Syntroleum management notes that in the "real world," yields are somewhat different. Further, Syntroleum's ATR process yields the "perfect"  $\text{H}_2$  to  $\text{CO}$  ratio of 2:1. Their calculations are as follow:

### SYNTHESIS GAS COMPOSITION

(Percent yield based upon methane feed)

	$\text{H}_2$	$\text{CO}$	$\text{CO}_2$	Total
Steam reforming	75	15	10	100
Partial oxidation	62	35	3	100
ATR with air	34	17	2	53*

\*Difference between 100 and sum of  $\text{H}_2$ + $\text{CO}$ + $\text{CO}_2$  of 47% is nitrogen.

Source: Syntroleum

It is noteworthy that while we talk about "steam methane reforming" as distinct from POX, in modern applications, steam is used in both approaches. In the case of steam reforming, large quantities of steam and the natural gas feedstock are pumped into the syngas reactor. In POX, a small amount of steam is pumped into the syngas reactor. Oxygen is also introduced and this causes oxidation that gives off a tremendous amount of heat—more than 2000 degrees Fahrenheit. Therefore, in the POX approach, no external burners have to be used to provide heat to the process.

In addition to these two primary approaches, variations are found. The Syntroleum process utilizes what the company calls an "autothermal reformer" or "ATR." ATR combines POX with steam reforming. Syntroleum's ATR process uses air rather than pure oxygen.

Exxon describes its syngas step as "a proprietary fluid-solid system that catalyzes syngas in a novel fluid bed reactor system...both partial oxidation and steam reforming reactions occur simultaneously...[which] increases thermal efficiency."

The table that follows summarizes the syngas processes used by the different "players" in the FT field. (It should be noted that "off-the-shelf" technology is readily available in all of these categories so, in essence, all companies can use all technologies. The listing below presents the companies' preferred primary actual or anticipated syngas technology, which in some cases, as noted, are proprietary).

Syngas Process	Company
Steam reforming	BP† Rentech Sasol
Autothermal reforming	Syntroleum*† *With air rather than oxygen.
Partial oxidation (POX)	Exxon*† Rentech Sasol Shell† *With proprietary catalyst. †Proprietary.

So what are the pros and cons of the various approaches? As the prior discussion touched on, external heat must be applied in steam reforming. This heat has a cost and further, a lot of it may be lost unless additional process equipment is added to capture the heat and reuse it. However, steam reforming, using a nickel-based catalyst, is a well-developed and widely-used process for production of synthesis gas. Further, it is a mature technology and the required process equipment is available worldwide from a number of companies. Looking at it from the standpoint of POX, partial oxidation is more thermally efficient than steam reforming and thus lowers the amount of feedstock required per unit of final production but it has a higher capital cost. Normally, POX requires a process unit to create a high purity stream of oxygen and these are very expensive. Further, pure oxygen is a very reactive element and dangerous explosions can occur<sup>21</sup>.

Syntroleum's unique approach of using air instead of oxygen addresses the cost and safety issues of traditional POX as the oxygen unit is done away with but normally, creates its own problems—mainly a large amount of nitrogen that must be dealt with. (Syntroleum has apparently turned that "problem" into an advantage as will be discussed later).

<sup>21</sup> For instance, as noted earlier, on Christmas day, 1997, the oxygen unit in Shell's "SMDS" plant in Bintulu Malaysia, a 12,500 barrel per day gas-to-liquids plant, blew up due to contaminants getting into a section of the oxygen making unit. The contaminants apparently came from smoke from local forest fires. While there were no deaths and few injuries, the entire GTL plant was disabled.

POX also has a drawback in that the carbon atoms can "coke up" (forming soot) which is a process where the carbon atoms bind only with other carbon atoms and solid coke results which must be disposed of or dealt with in some fashion.

On the other hand, POX is a more versatile process in that it can handle a variety of feedstocks (natural gas, coal, bitumen, coke, resid, biomass, etc.<sup>22</sup>) whereas steam methane or autothermal reforming, generally can only be applied to natural gas and further, natural gas which does not contain sulfur<sup>23</sup>. The nickel catalyst used in steam reforming is "poisoned" if it comes in contact with sulfur.

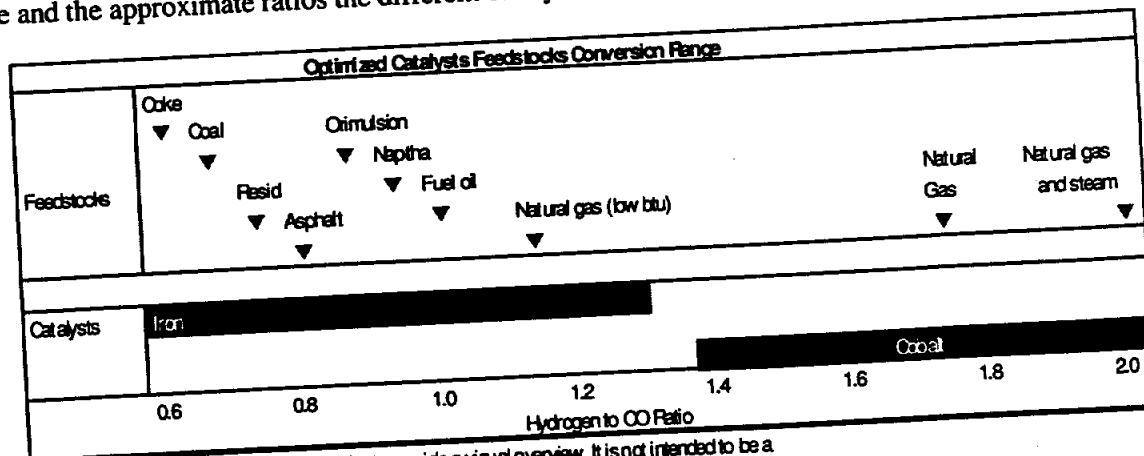
Another factor that may drive the decision as to whether to use steam reforming or POX is the ratio of hydrogen to carbon monoxide ( $H_2:CO$ ) that is produced in the process of making syngas as this ratio is critical for several reasons. As previously mentioned, adjustments can be made by adding  $CO_2$  in the case of steam methane reforming in order to decrease the ratio from around 5:1 towards the desired 2:1 and in the case of POX, steam and/or water may be introduced in order to raise the ratio towards the desired 2:1. In autothermal reforming, the ratio can be adjusted with steam and/or  $CO_2$ . In general,  $CO_2$  recycling is substantially more expensive than adding steam and this additional cost must be considered against all of the other cost/benefit factors involved.

Other  $H_2:CO$  considerations are: (1) The ratio determines what catalyst can be used in the ensuing Fischer-Tropsch reaction, (2) it affects the product slate produced in the FT reaction, and (3) it can create disposal problems.

An additional consideration is "methane slip" which is when some  $C_1$  to  $C_4$  molecules are not chemically altered in the syngas step. This is undesirable and the efficacy of the syngas step is measured in part by the degree of methane slip.

While we have not yet talked about the catalysts that are used in the FT process and will do so in the next section of this report, at this point it is necessary to introduce the issue. As mentioned earlier, two basic types of catalysts are used in the FT reactor: cobalt and iron.

The graph that follows shows the approximate hydrogen to CO ratios the different feedstocks generate and the approximate ratios the different catalysts can convert to FT products.



Note: This is a rough approximation in order to provide a visual overview. It is not intended to be a technically accurate depiction of scientific reality.

<sup>22</sup> This statement is only true if we consider gasification to be POX, which, for purposes of this report, is sufficient though process engineers would differentiate the two.

<sup>23</sup> Natural gas or oil, that does not have any sulfur in it, is referred to in the oil and gas industry as being "sweet". Conversely, if they do contain sulfur, they are referred to as "sour."

As the "cartoon" on Page 18 indicates, cobalt is favored at a higher ratio and iron, at a lower ratio. However, both can operate across the entire range if process adjustments are made. Iron requires substantial CO<sub>2</sub> recycle at the higher ranges, cobalt requires a water-gas shift (or some other such) process at the lower ratios. It is beyond the scope of this report to delve further into these processes except to say that each has a cost. Whether one would use cobalt catalyst for coal or iron for natural gas generally will come down to the question of overall economics. The Germans used cobalt for coal and Sasol's iron catalyst is being used to convert natural gas to liquids at the Moss gas plant, so obviously, there is flexibility.

As to product slate, the ratio of H<sub>2</sub> to CO will affect the chemical composition of the FT products. This will be discussed later in this report after we have introduced certain key terms and concepts necessary to understand the differences.

Finally, as to disposal problems, the syngas step produces hydrogen and carbon monoxide of course—these are the desired products—but, it also produces CO<sub>2</sub>, as noted earlier, steam and possibly pure carbon in the form of coke. The steam is removed by cooling and condensation. CO<sub>2</sub> may be recycled or separated out by another chemical reaction, and carbon may be broken up by adding more steam and/or washed out with the water that results from cooling the steam.

The table that follows summarizes the advantages and disadvantages of the various synthesis gas technologies.

### Pros (+) and Cons (-) of Various Syngas Generation Approaches

Steam Methane Reforming (SMR)	Partial Oxidation (POX)	Autothermal Reforming (ATR)
+Largest # units in operation	—Fewer units in operation	—Few units in operation
+No oxygen unit required	—Oxygen required	—Oxygen required†
—Runs at lowest temperature	+Runs at high temperature	+Runs at lower temp. than POX
+No coking	—Coking a problem	—Coking a problem
—Higher H <sub>2</sub> to CO ratio	—Lower H <sub>2</sub> :CO ratio	+Favorable 1.6-2.65 H <sub>2</sub> to CO
—Needs external heat	+Makes own heat	+Makes own heat
—Needs steam	+No steam*	+No steam*
—Higher CO <sub>2</sub> produced	+Lower CO <sub>2</sub> produced	+Lower CO <sub>2</sub> produced
—CO <sub>2</sub> recycle expensive	+Low or no CO <sub>2</sub> recycle	+Low or no CO <sub>2</sub> recycle
—No sulfur can be tolerated	+Sulfur taken out after	—No sulfur can be tolerated
—Only natural gas feedstock	+Wide range of feedstocks	—Only natural gas feedstock
—Catalyst required	+No catalyst	—Catalyst required
—Start/stop difficult	+Start/stop easier	+Start/stop easiest
—More methane slip	+Less methane slip	+Less methane slip

†Syntroleum ATR uses forced air rather than oxygen bypassing need for oxygen unit.

\*However, steam generally used to reduce coking, but far less than SMR.

Source: Paper given by Howe-Baker Engineers, Inc., Bob Tindall and Andy Crews at San Antonio GTL meeting in May 1998. Also, additional input from Rentech and Syntroleum

Which approach of the three above that is used will depend ultimately on an analysis of a number of factors. No one approach is necessarily "better" than any other, though one may be better than another given a specific application.



## FT CATALYSTS

As we briefly mentioned earlier, there are two basic types of catalysts used in the Fischer-Tropsch reactor: cobalt and iron. In the history of FT, BASF reported the first use of catalysts to convert syngas to synfuels using, and receiving patents on, metal-oxide catalysts in the 1910s. In the 1920s, Fischer and Tropsch reported their success in using both iron and cobalt catalysts. Further refinements by German scientists were made in the 1930s leading to the deployment of nine commercial plants.

Improvements in iron-based catalysts and cobalt's scarcity in the late 1930s led to iron's use in the German war-time plants in the 1940s. Sasol adopted the German iron-based approach and deployed it in its plants. Today, the use of iron-based catalysts is Sasol's main technology though Sasol is reported to be pursuing cobalt-based catalyst development.

Rentech has focused its R&D on iron catalysts and used its proprietary iron catalyst in its Synhytech plant in Pueblo, Colorado. The technology licensed by Rentech to Texaco is an iron-based catalyst technology.

Both Shell and Exxon have focused primarily on cobalt catalysts and have numerous patents relating to their catalysts. The Shell Bintulu plant used a cobalt catalyst as did Exxon's Baton Rouge pilot plant. Syntroleum's FT technology is also cobalt-based.

As we discussed earlier, the choice of catalyst is a key variable in determining what feedstocks can be converted to synfuels. Traditionally, cobalt is more likely to be used with natural gas while iron-based catalysts are more likely to be used with "heavier" carbonaceous feedstocks.

Other catalyst pros and cons are presented in the table that follows:

Cobalt	Iron
Higher conversion rate	Lower conversion rate
Less tolerant of sulfur.	More tolerant of sulfur.
Longer catalyst life ( $\pm 4$ years)	Shorter catalyst life ( $\pm 4-8$ weeks)
Raw material more expensive	Raw material less expensive.
Some product supply interruption and price risk. <sup>24</sup>	Iron freely available
Cobalt catalysts typically require the use of other rare and/or expensive metals such as ruthenium, rhenium, and platinum. (These are referred to as "promoters.")	Iron catalyst "promoters" currently less involved than cobalt, however, this may change over time as more exotic approaches pursued.
Spent cobalt catalyst is considered a hazardous waste. However, this may not really matter as it can be regenerated and reused.	Spent iron catalyst not a hazardous waste. Not currently economical to regenerate iron catalyst.
Cobalt produces more paraffinic <sup>25</sup> products.	Iron produces more olefinic products <sup>26</sup> .

As was the case when we discussed the synthesis gas step, there are various pros and cons to be considered when choosing a catalyst. Neither is necessarily better. Which is better will depend on a number of factors specific to the particular application and location.

<sup>24</sup> Per the U.S. Geological survey, world reserves of cobalt are around 4 million tons. Of these, 2 million are in Zaire and 1 million are in Cuba. Zambia has 360,000 tons of reserves and Australia, 270,000 tons. World production of cobalt in 1997 was 27,000 tons implying a remaining reserve life of almost 150 years, or in other words, no current shortage.

<sup>25</sup> We will define "paraffinic" and explain its import later in this report.

<sup>26</sup> We will define "olefinic" and explain its import later in this report.

## FT REACTORS

Just as there are a plethora of different approaches to making synthesis gas there are a number of ways to make Fischer-Tropsch products. Not only the choice of catalysts is important, the way the catalysts are deployed or brought into contact with the syngas is an area of great diversity. Before we get into that however, it may be helpful to understand that regardless of what approach we take, fundamentally, both the catalyst and syngas have to be brought into contact in some kind of reactor. Refiners often speak of the area where catalysts interact with hydrocarbons as "beds" though as we will see, in some FT reactors that concept seems to make sense and in others, it does not.

The basic different kinds of "beds" are:

- Fixed beds
- Fluidized beds
- Fixed fluidized beds
- Slurry (referred to as a slurry reactor, or three phase reactor, not a "slurry bed")

Fixed bed reactors contain hundreds to thousands of tubes into which the catalyst, which is generally in pellet form, is packed. The syngas is pumped through the top of the tubes and reacts with the catalyst and out the bottom, flows the FT products.

In a fluidized bed reactor, there really is no "bed." The catalyst in powder form is placed in the reactor vessel. There are tubes but these are used for cooling. The syngas is introduced into the bottom of the reactor and "fluidizes" the catalyst in the sense that air blowing into a room would carry dust particles aloft. Catalyst is recycled in this approach.

In a fixed fluidized bed configuration, the catalyst is packed into the sloped bottom sides of the reactor. As syngas is introduced, it sets the powdered catalyst in motion as in the fluidized bed case but as the catalyst is more packed in the bottom of the reactor then farther up along the sides of the reactor, the movement of catalyst is more restricted in the bottom than the top. In essence, some of the catalyst is fairly fixed and some is fairly fluid, hence the name "fixed fluidized."

Slurry reactors are quickly becoming the preferred alternative. A slurry reactor is a vertical vessel in which the fine powdered catalyst is suspended in a bed of molten wax. The syngas is introduced into the bottom of the reactor and some FT products emerge from the top and some also come off the side of the reactor. The FT product stream is filtered from the wax/catalyst slurry.

The table that follows shows which approaches companies with FT technology use.

"Beds"	Company
Fixed	British Petroleum Shell Sasol Syntroleum
Fluidized	Sasol Syntroleum
Fixed fluidized	Sasol
Slurry	Exxon Rentech Sasol Shell Syntroleum

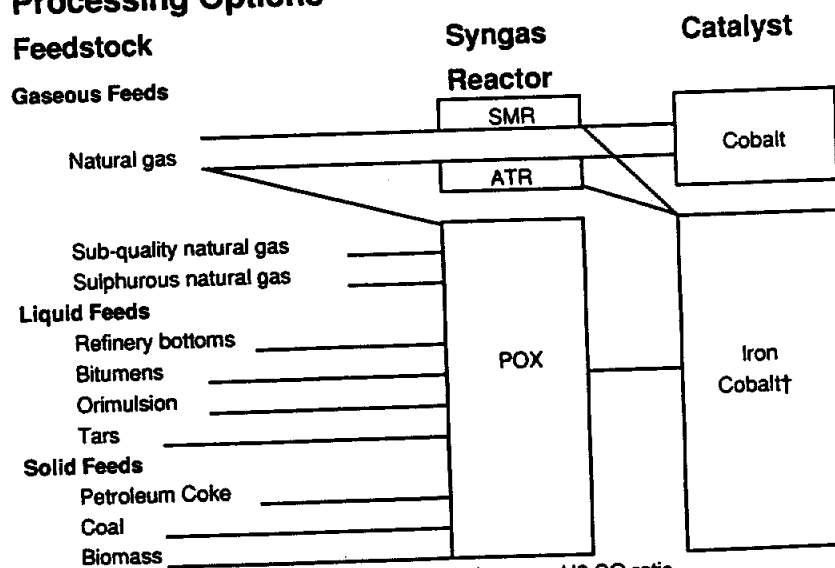
We should add that Syntroleum is developing what it refers to as the "HMX" reactor, a proprietary multi-phase reactor. Syntroleum believes its HMX reactor will be the most commonly selected reactor design because of its high capacity and simpler operation.

The *pros* and *cons* of the various types of FT reactors are:

- Much higher throughput with fluidized or slurry. Fixed bed reactors are "heat transfer limited" which means that they produce less liquid product because, as they are more difficult to cool, they must be run at a lower throughput rate in order to maintain proper temperature control.
- Can change out catalyst with slurry and fluidized bed while operating, can't with fixed bed.
- Wax/catalyst separation is a major problem in a slurry reactor.
- It is thought that maximum capacity with slurry reactors is around 10,000 barrels per day of FT products. Projects larger than that will have to be accomplished with reactors operating in parallel. (However, Exxon indicated to us that it expects to achieve slurry reactors of significantly larger size than 10,000 barrels per day).
- Fixed bed reactors can develop "hot spots" as they have a similar heat transfer problem as described above. The immediate detection of such a hot spot is difficult and expensive raising safety issues.
- Fluidized beds must be run at high temperatures in order to produce the desired FT product mix and keep catalyst working correctly.
- Slurry reactors afford best control over temperatures.
- Slurry reactor is generally the lowest cost option.

It should be clear from all of this discussion of how synthesis gas is made, the different FT reactor options, and the two basic types of catalysts that can be used in the FT reactor that there are very specific options available for processing the different potential FT feedstocks. The schematic below sets the various options.

### Fischer-Tropsch Feedstock Processing Options



† If water gas shift unit or other process used to increase H<sub>2</sub>:CO ratio.

Also, sulfur must be removed.

\*SMR\* - Steam methane reforming

\*ATR\* - Autothermal reforming

\*POX\* - Partial oxidation

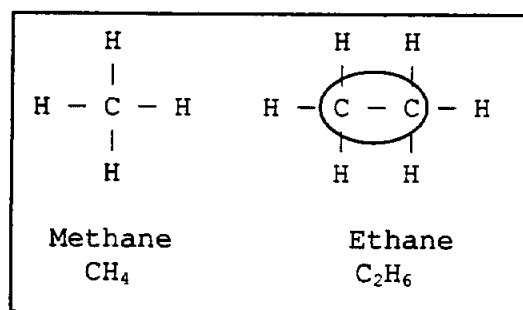
What we hope to point out by the foregoing technical discussion is not that there is one best technology but that there are many decisions that can be made and must be made in deciding on what technical route to take to make FT products. The decision matrix will be driven by a number of considerations including available feedstock, FT products desired, site power availability (electricity, steam, hydrogen), plant size, etc.

## REFINING AND PETROCHEMICAL PRIMER

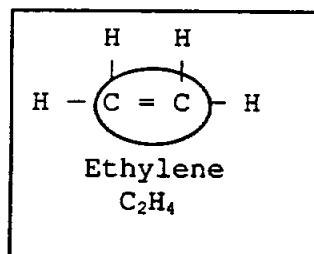
Before we get into the next section of the report, "Fischer-Tropsch Products," unfortunately, it is going to be necessary to delve into a little more chemistry and define some commonly used terms in the refining and petrochemical industries.

One thing that should become clear from all of this is a central point that we are trying to make in this report—Fischer-Tropsch is fundamentally about refining. We believe it has been narrowly viewed as an "upstream" technology; that is, a technology to solve the problem of how to deal with stranded gas (which we discuss later). While this is true, by the time FT truly comes into its own, we believe the technology will be more correctly perceived first and foremost as a refining technique.

Earlier we mentioned that hydrocarbons are made up of various combinations of carbon atoms and hydrogen atoms. These carbon atoms, according to the laws of nature, always want to combine with four other atoms (see the methane molecule presented in the box below). Those "other atoms" can be other carbon atoms. The ethane molecule in the box shows the connection (or "bond") between the two carbon atoms (circled).



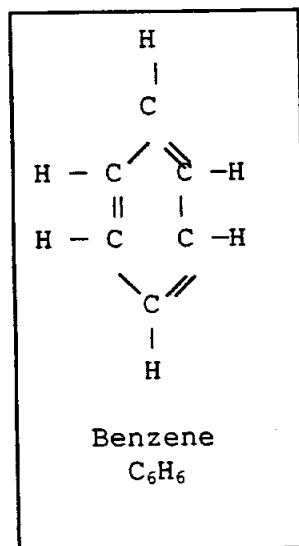
Another feature of carbon atoms is that there may be two bonds between the same carbon atoms as is the case with ethylene as presented in the box below (double bond circled).



Now for the new terms: when the carbon atoms have only single in-line bonds, we call them "paraffins." The simple distilling process described earlier basically operates on and separates out paraffins from one another. Hydrocarbon molecules with double carbon bonds, like ethylene, are called "olefins."

The double carbon bond feature of olefins can be considered to be the chemical equivalent of a dividing line between petroleum products (paraffins) and petrochemicals (olefins).

In addition to these kinds of hydrocarbon molecules—paraffins and olefins—which are generally referred to as "straight-chain" molecules, there is a whole family of carbon-based molecules where the carbon atoms are connected to one another to form a circle. Benzene is a good example of these so-called "cyclic" molecules. Benzene is represented in the box below.



One of the reasons we have chosen benzene as an example of a cyclic hydrocarbon molecule is that any hydrocarbon that has a benzene "ring" in it is called an "aromatic" and this is a term you will run into in the next section of this report.

Finally, there are a family of hydrocarbons with one or more oxygen atoms in their structure. These are called "oxygenates" and are further broken down into alcohols and ethers. Methanol and ethanol are examples of alcohols.

Just as all of these families of carbon-based products can be made from crude oil, they also can theoretically be made from natural gas or coal. Now that we know what "olefins" and "paraffins" are, we can finish the discussion of the pros and cons of reactors and catalysts. Earlier, when discussing the hydrogen to CO ratio in the section on making syngas, we noted that the ratio affected the FT product slate. Simply put, a lower  $H_2:CO$  ratio produces more olefinic products and a higher ratio produces more paraffinic products.

Further, as reforming, either steam methane (SMR) or autothermal (ATR), produce a higher  $H_2:CO$  ratio, by definition, these syngas processes will tend to produce a more paraffinic FT product slate. (Though the catalyst choice is also a factor in the olefinic versus paraffinic nature of the FT product slate).

Now, let's see what products will be made from Fischer-Tropsch.

## PRODUCTS

Throughout this report we have been referring to "Fischer-Tropsch products." What are these products and why is it worth such an effort to make them? That is the topic of this section.

## FT BY-PRODUCTS

First, let's talk about what comes out of the FT reactor, which we need to dispose of or recycle (Let's refer to these as "Fischer-Tropsch by-products" or "FT by-products.") The FT reactor produces water<sup>27</sup> and not an insignificant amount. Conventional FT with an iron catalyst makes about 7/10ths of a barrel of water for each barrel of FT products. Cobalt FT makes about 1.1 to 1.3 barrels of water for each barrel of FT products.

Another interesting aspect of the potential for Fischer-Tropsch technology is that in areas of the world where water is scarce and natural gas is not (like the Middle East), heat produced by the process can be used to desalinate sea water. Alternatively, part of the water can be recycled to make steam in the syngas unit and for cooling in both the syngas and FT step of the overall process.

In addition to water, the FT reactor produces what is referred to as "tail gas" which contains hydrogen ( $H_2$ ), carbon monoxide (CO), carbon dioxide ( $CO_2$ ), and some light hydrocarbon gases such as methane ( $CH_4$ ), ethane ( $C_2H_6$ ), propane ( $C_3H_8$ ), and butane ( $C_4H_{10}$ ). Excess hydrogen can be stripped out of the tail gas through a membrane system and sold or recycled either to the syngas reactor or to the FT reactor to increase product yield. (Any excess hydrogen can be used as a fuel in the syngas step or for the production of electricity.)

Carbon dioxide made in the FT unit can also be separated from the tail gas and recycled to the syngas unit to increase the carbon conversion efficiency of the entire process<sup>28</sup>. Carbon monoxide can not be readily separated from the tail gas so it, and the gaseous tail gas hydrocarbons, can be recycled to the syngas unit as either feedstock or to produce power.

In the Syntroleum process, as compressed air is a source of oxygen, significant amounts of nitrogen must move through the system.<sup>29</sup> This nitrogen emerges from the FT unit in the tail gas and Syntroleum's approach to getting rid of it is to use the tail gas as feedstock to a specially designed turbine (that can burn the low Btu tail gas) which powers the air compressor. (A significant aspect of the Syntroleum process is that no other recycle loop is required.) The efficacy of Syntroleum's use of air rather than oxygen in the syngas step has some doubters. Several studies have been done questioning whether the benefits will in fact outweigh the costs. Ultimately, the marketplace will make this decision (and to some extent, perhaps already has given Syntroleum's success in licensing its approach).

## FT PRODUCTS

After accounting for all of the by-products, what's left are two basic product categories: (1) synthetic oil and (2) petroleum wax (which is solid at room temperature) Depending on a host of factors including:

- the syngas hydrogen to carbon monoxide ratio,
- the FT reactor design,
- the catalyst, and
- the temperature and pressure conditions in the FT reactor,

the mix of solid (wax) to liquid ratio varies around 50/50.

<sup>27</sup> Mixed with some oxygenates in the form of alcohols.

<sup>28</sup> This is true primarily when iron-based catalyst is used as cobalt-based catalysts generally make very little  $CO_2$ .

<sup>29</sup> As previously noted, air contains about 20% oxygen and 80% nitrogen. Thus, in the Syntroleum process, it would appear that five times as much volume in the form of air would be going into the FT reactor (1-part oxygen and 4-parts nitrogen) as in the processes that use pure oxygen. However, that is not the case as, the relative volumes of nitrogen and oxygen are altered in the syngas step such that the percentage of nitrogen in the syngas is only 47%.

The FT products are totally free of sulfur, nitrogen, nickel, vanadium, asphaltenes, and aromatics that are typically found in crude oil. Further, the products are almost exclusively paraffins and olefins with very few, or no, complex cyclic hydrocarbons or oxygenates which require further separation and/or processing in order to be usable end-products. The absence of sulfur, nitrogen, and aromatics substantially reduces harmful emissions.

The synthetic oil produced in the FT process has a gravity<sup>30</sup> of around 60° (versus around 36° for light crude oil and around 60° for gasoline). It can be transported in the same ships in which crude oil is transported and by the same pipelines—in short, it can use the same transportation infrastructure as conventional oil. FT synthetic oil can be distilled into two major fractions, naphtha and distillates. Naphtha is a light product with five to nine carbon atoms ( $C_5$  to  $C_9$ )<sup>31</sup>. Distillates have 10 to 20 carbon atoms.

The principal use of conventional naphtha made from crude oil is to make gasoline. The balance is used predominately as a chemical feedstock. About half of the naphtha that goes to make petrochemicals goes to ethylene and one half to make aromatics. FT naphtha will more than likely be used predominately to make ethylene due to the FT synfuel's lack of aromatics which are favored for making gasoline (and obviously, for making aromatic hydrocarbons). In fact Shell, in describing the naphtha produced at its "SMDS" plant in Bintulu says "the...naphtha fraction is completely paraffinic and therefore makes an ideal cracker feedstock for ethylene manufacture. The absence of aromatic structures...gives rise to up to 10% higher than conventional ethylene yields..." Until the explosion, the Shell plant was selling naphtha in Singapore for ethylene manufacture.

The middle distillate cut consists of three further fractions, jet fuel, kerosene, and diesel fuel.<sup>32</sup> All three products have excellent properties. Sasol is selling jet fuel currently from its plants in South Africa. The product with perhaps the brightest future though is diesel for use as a road-use fuel. (It should be noted that diesel is often referred to as "gasoil.")

The attraction of FT diesel relates to its purity. Shell notes that California's Air Resources Board ("CARB") specs for diesel, the strictest in the world, require a minimum cetane<sup>33</sup> value of 48 and Shell's SMDS diesel has a cetane of 76. Further, the CARB standard for sulfur is that the diesel has to contain less than 500 parts per million and SMDS diesel has no detectable parts per million. The maximum aromatics percentage in CARB diesel is 10%, SMDS diesel has no detectable aromatics. While Shell's SMDS plant was in operation, it was selling diesel to Tosco Corporation which Tosco used as a blendstock to improve the quality of the diesel it refined in California. Rentech actually had its FT diesel tested by the California Air Resources Board for use in California (low altitude) and by Environmental Testing Corporation in Colorado (high altitude). Rentech's results were consistent with SMDS diesel in all respects. It is expected that all FT diesel will perform similarly.

Another potential positive aspect of FT diesel is the possibility that it may be able to be used after distillation with no further processing. There is some considerable debate over the issue, and the debate relates to the fact that FT diesel contains olefins and in a conventional refinery producing conventional

<sup>30</sup> "Gravity" used in this context refers to weight by volume. Further, the specific measure of gravity used in the petroleum industry is gravity as defined by the American Petroleum Industry. Under this approach, water, for instance, has a gravity of 10°.

<sup>31</sup> Remember, generally, hydrocarbons with fewer than five carbon atoms are a gas, more than four carbon atoms and hydrocarbons exist in a liquid state, and more than 20 carbon atoms produces a solid (assuming, in all cases that we are at room temperature and pressure).

<sup>32</sup> It should be noted that the third step in the overall FT process is distillation of the FT fuels into different fractions. While one could just distill the FT "oil" into naphtha and distillates, very little incremental equipment is required to break the distillates down into jet fuel, kerosene, and diesel and therefore, this is likely to happen.

<sup>33</sup> "Cetane" is the primary measure of diesel fuel quality. It is essentially a measure of the delay before ignition. The shorter the delay—the better—and the higher the cetane number

diesel, the olefins have to be split out<sup>34</sup> as they cause problems during fuel use. However, due to the purity of FT diesel and the specific type of olefins produced, it is believed that not only the olefins and other oxygenates in the fuel might not be a problem, they might in fact produce a better fuel.

For instance, testing by third parties of Rentech's unhydrogenated diesel fuel has tended to confirm this hypothesis. In fact, Rentech has applied for and been granted three U.S. patents on the use of its diesel fuel, either as a blendstock, or for use, unblended. While these patents afford Rentech some protection from other companies producing FT diesel with an iron-based catalyst, it does not impinge on Syntroleum or others using a cobalt-based catalyst.

In fact, Syntroleum is exerting considerable effort to position its fuels in the market place. Excerpts from a Syntroleum press release issued October 13, 1998, best tell the story:

Syntroleum Corporation...announced today that it has retained Southwest Research Institute to test a new family of synthetic fuels being developed by Syntroleum for use in diesel engines. These tests follow successful preliminary research conducted by Syntroleum and the University of Kansas and will form the basis of the company's application for certification of the fuels under the Energy Policy Act (EPACT) of 1992.

The goal of the program is to produce synthetic diesel fuels that meet the most stringent U.S. environmental regulations and that qualify as alternative fuels under EPACT.

Syntroleum also announced that it has entered into a separate agreement with the University of Kansas Center for Research, Inc. (CRINC) to conduct further tests on Fischer-Tropsch (FT) fuels in compression ignition (diesel) engines.

The agreement, which was signed September 15, 1998, follows a cooperative fuels testing and development effort that began in the summer of 1997. Objectives of the ongoing work are to determine the FT middle distillates most suitable as fuels in diesel engines without the need for further refining, determine the merits of these fuels compared to conventional diesel fuel, and determine which FT fuel would best qualify as an alternate fuel under the guidelines set out by the Environmental Protection Agency (EPA) and the Department of Energy (DOE).

Under EPACT, the federal government and many large cities are required to convert an increasing percentage of certain fleets (i.e. buses, mail trucks, garbage trucks and other vehicles) to alternative fuel vehicles (AFVs), which are defined as vehicles running on non petroleum-based fuels. DOE modeling information suggests that fleet use of alternative fuels could reach 600,000 barrels per day, or as much as 38 percent of all light duty vehicle fuels, by 2010.

This assumes, however, that adequate sources of alternative fuels are available. Currently, less than three percent of total highway transportation fuels consumed in the U.S. are alternative fuels. This figure is low because the majority of highway transportation vehicles are diesel powered and there is virtually no alternative fuel available for them.

Biodiesel, which was approved as an alternative fuel in 1996, is currently produced in very limited quantities reportedly selling for about \$3 per gallon. With the exception of biodiesel, all other available alternative fuels require major changes in vehicle power plants, or new engines altogether.

Additionally, all other currently available EPACT fuels require completely separate distribution infrastructures. Synthetic fuels produced using the Syntroleum Process would not require any modification of engine type, and could use existing channels of distribution.

<sup>34</sup> Through a process called hydrogenation which introduces hydrogen in order to get the olefins to split out from the paraffins. As mentioned in the previous section of this report, olefins contain double carbon bonds. Introducing hydrogen to react with the olefins causes the double bonded carbon atoms to bond with hydrogen instead "breaking" the double bonds thus resulting in paraffins.



"The U.S. market for synthetic fuels could offer a significant new opportunity for Syntroleum licensees," stated Mark Agee, Syntroleum president and chief operating officer. "Our research in this area could mark the beginning of the first designer fuels for the new engine designs that are just around the corner."

It should be clear from the foregoing that there is great promise for FT diesel and FT diesel holds great promise to help the environment.

## FISCHER-TROPSCH FEEDSTOCKS

### OVERVIEW

While the use of natural gas as a feedstock for Fischer-Tropsch has gotten the most attention, as this report has made clear, FT can process a wide range of carbonaceous materials including coal and petroleum coke and other "bottom of the barrel" feedstocks. In this section, we will discuss the most important of these starting with natural gas.

### NATURAL GAS

**Stranded Gas:** The most recently compiled data according to the Oil & Gas Journal indicates total worldwide gas reserves of some 5,100 trillion cubic feet (tcf). Of that, industry analysts have estimated that some one half is "stranded" which means there is no local market for the natural gas (which we will also refer to as "gas.")

Given that the FT conversion rate of natural gas to "synthetic oil" is around 10 to one (that is, 100 million cubic feet of natural gas "makes" 10,000 barrels of synthetic oil), that stranded gas could make around 250 billion barrels of synfuels—almost equivalent to all of the estimated oil reserves of Saudi Arabia which has the world's largest reserve of conventional oil.

In addition to the sheer magnitude of the world's natural gas, the rate at which that gas has been being found is noteworthy. The Oil & Gas Journal estimated recently that about half of that 5,100 tcf has been discovered since 1976 (which means that the rate at which stranded gas is piling up is accelerating too).

The natural gas reserves on Alaska's North Slope are a classic case of stranded gas. Arco's stranded gas reserves there alone constitute some 13 trillion feet. The entire North slope is believed to have around 35 trillion cubic feet—enough gas to make almost 480,000 barrels per day of synthetic oil assuming a 20-year field life.

The size of stranded natural gas fields is also important when considering FT as a means of monetizing natural gas. The table that follows sets forth the numbers of fields of various sizes.

## Natural Gas Fields Outside of the U.S.

Reserves			Production*		Fields	
<i>Trillion cubic feet</i>			<i>Millions of cubic feet</i>			
Between	50	and 500±	4630	to	46296	15
Between	5	and 50	463	to	4630	78
Between	1	and 5	93	to	463	234
<i>Subtotal</i>						327
<i>Billion cubic feet</i>						
Between	500	and 1000	46	to	93	269
Between	250	and 500	23	to	46	276
Between	100	and 250	9	to	23	475
Between	1	and 100	0	to	9	1195
<i>Subtotal</i>						2542
Less than	1		0		0	1913
<i>Total</i>						4455

Source: Petroconsultants and Syntroleum

\*Potential daily production. Howard Weil estimate based on 30-year field life.

The foregoing reserves and fields data were compiled by Petroconsultants for Syntroleum for use in illustrating the flexibility of Syntroleum's GTL plants. Shell and Exxon have discussed plants in the 50 to 100 thousand barrel per day range which would require natural gas input of 500 to 1000 million cubic feet per day meaning that only the stranded fields in the top two tiers of gas fields outside of the U.S. would be accessible. Syntroleum's plan is to build plants of varying sizes including smaller plants; 2000 barrels per day or so which could access all but the bottom tier of the stranded gas fields outside of the U.S. Rentech also is targeting smaller plant sizes.

As previously described, Syntroleum's syngas step uses air rather than oxygen and thus, by eliminating the need for an oxygen-making unit, reduces the capital costs associated with making syngas which may reduce the overall costs involved in making FT products to a level where small plants are economically viable.

Rentech's approach to small plants is two-pronged. First, Rentech proposes small plants which are primarily focused on making wax in markets like India that are net importers of wax and second, Rentech is pursuing a method for making syngas that, like Syntroleum, avoids the need to make oxygen (though with a completely different technology than Syntroleum's—see the Research & Development section of this report).

It should be noted that there are other technologies to produce stranded natural gas fields such as liquefying the natural gas (LNG) which we will discuss in more detail later.

**Associated Gas:** "Associated gas" is natural gas occurring in stasis with and produced along with crude oil. Such gas occurs all around the world and in effect, is stranded if there is no market for the gas. Associated gas is often flared or re-injected. The former is wasteful and environmentally a poor option. The latter is expensive.

In Nigeria, and to some extent, in the rest of West Africa, flaring of natural gas is prohibited in new projects and will be phased out in existing production by 2010. In an article in a recent edition of Upstream Magazine, it was reported that Elf Aquitaine was considering FT as the solution to the associated gas at its massive Girassol discovery in Angola. Marathon also is reportedly considering FT as a solution to associated

gas at its Sakhalin Island project in Russia. We estimate that the cost of re-injection of associated gas at Sakhalin would be around \$0.30 per thousand cubic feet—that equates to a negative cost of \$3.00 per equivalent barrel of oil.

It is also important to note (and to consider in the economics of a gas-to-liquids project) that one of the important benefits of producing stranded gas which is also associated is that certain volumes of oil can not be produced except if the associated gas is produced. In the case of Alaska's North Slope, the Department of Energy estimates that by recovering all of the natural gas there, an additional 1 billion barrels of oil would be produced.

**Substandard Gas:** A study conducted in the early 1990s by the Gas Research Institute determined that 34% of the raw, non-associated natural gas in the lower 48 U.S. states is sub-quality which is defined as containing excessive amounts of carbon dioxide, nitrogen, and hydrogen sulfide (about 50 trillion cubic feet of total reserves).

**Hydrates:** Hydrates are essentially frozen natural gas (methane). The U.S. is believed to have massive reserves offshore the East Coast. While conversion of hydrates to FT products may be currently considered as some sort of Rube Goldberg fantasy, the science is solid and we believe that it will eventually happen.

## LIQUIDS

Carbon bearing solids and liquids also may be used as FT feedstocks and movement is afoot on that front. Rentech Inc., recently licensed its proprietary Fischer-Tropsch technology to Texaco giving Texaco the exclusive right to use or sub-license Rentech's FT technology to convert liquids and solids (such as refinery bottoms) to FT products. In addition, Texaco may use Rentech's FT technology to convert natural gas to liquids for its own account. (It should be noted that under the terms of Texaco's arrangements with Syntroleum, they also could use Syntroleum's FT technology in a refinery application.)

Rentech's technology, like all FT technology requires the input of synthesis gas—a mixture of carbon monoxide and hydrogen. In a refinery setting, Texaco's gasification technology creates that synthesis gas from petroleum coke, residual oil, asphalt, etc., at a hydrogen to CO<sub>2</sub> ratio ideal for Rentech's FT process thus avoiding the need for additional capital expenditures for equipment to modify the ratio.

Texaco has been in the gasification business for some 50 years and has licensed over 250 gasifiers around the world. In a refinery setting, the rationale or attractiveness of a Texaco gasifier is that refiners can convert the low, no, or negative value bottom-of-the-barrel products into synthesis gas that can then be converted to electrical power. This electrical power can be utilized to power a refinery and/or be sold to local power companies or end-users. Texaco refers to its gasification system as "Integrated Gasification Combined Cycle" or simply, "IGCC."

According to the Gasification Technologies Council, a trade organization, Texaco is currently in the design or construction stages on 13 new gasifiers including three for Exxon—at Baytown Texas, in Singapore, and in Japan.

It should be noted that Exxon has a license agreement for the use of the Texaco Gasification Process. Under the terms of this agreement, Texaco has granted Exxon the right to use the Texaco process throughout Exxon's refineries and chemical plants worldwide. (As of the end of 1997, Exxon owned all or a part of 31 refineries and 56 chemical plants—not to mention Mobil's portfolio.)

The rationale of Texaco's licensing the Rentech Technology is that an FT unit using Rentech's Technology can be integrated into Texaco's gasifiers<sup>35</sup> and use the synthesis gas made by the gasifier in order to make FT Products.

An article July 1, 1997 in the "Energy Economist," a sister publication of the Financial Times puts it this way...

Refineries...are possibly the most suitable place to install an FT gas conversion facility, as much of the upgrading plant required for a stand-alone conversion plant will not be required, thus reducing capital costs. In addition, the refiner can extract full value from the FT diesel, because it is in the best position possible to blend the product into the refinery fuel pool. FT conversion will thus become a more elegant process option for refiners to meet the demanding specs for low sulfur and low aromatic diesel. In addition, as refiners are forced to process heavier and sourer crudes, an FT plant is another way of improving the overall efficiency of the refinery.

This capability gives the refiner the flexibility to vary the output of electrical power during periods when (a) electrical power may be worth less than FT products or (b) there is less, or no, demand for electrical power from local utilities or electrical power users. The best term we have heard in usage to describe the latter is "load leveler." The Rentech technology, when deployed in concert with a Texaco gasifier, has the potential to be a load leveler allowing the refiner to run the gasification/FT unit at a constant level (as refineries typically run at a constant level) and vary the mix of output between electrical power and FT products. For instance, during the day when electrical power usage is greatest, the unit would make more electricity and less FT products. At night, the ratio could be reversed.

An article authored by three Texaco employees<sup>36</sup> entitled "Coke Gasification Costs, Economics & Commercial Applications," describes the benefits of FT technology in a refinery and makes the important point that the process can be an add-on to an already gasifier-outfitted refinery.

New catalysts and reactor designs promise to make [FT technology] economically attractive...for syngas produced from coke or other low value domestic fuels. Preliminary reviews indicate a good rate of return on incorporating this [FT ] technology, even when done as a retrofit design... (emphasis added).

So far, we have focused on what problems a gasifier or a gasifier and an integrated FT unit solve. What of the opportunities? Here is where things get really interesting. In a paper given in San Francisco recently, Texaco employees involved in the company's gasification business<sup>37</sup> gave an example of a refinery gasification project they currently have underway where they were able to **increase refinery throughput by 40,000 barrels per day and run heavier, more sour, and cheaper crude** on a nominal 150,000 barrels per day by adding a deasphalter unit and gasification unit to debottleneck bottoms handling. The authors state **"the cost of the additional crude volume is approximately offset by the decrease in crude cost."** Further, diesel yield increased by 20,000 barrels per day adding \$400,000 per day of incremental revenue and the net value of the byproducts from the syngas (electricity, hydrogen, etc.) was \$300,000 per day. This project is expected to have a 2-year payback on the capital cost of \$500 million.

<sup>35</sup> To be absolutely accurate, it should be noted that under the terms of the Rentech/Texaco agreement, Rentech's FT technology can be used with gasifiers other than Texaco's.

<sup>36</sup> Fred C. Jahnke - Gasification Technology Manager, J.S. Falsetti - Senior Licensing Coordinator, and R. Fred Wilson - Director - Gasification

<sup>37</sup> "Heavy Oil Upgrading by the Separation and Gasification of Asphaltenes" by Paul S. Wallace, M. Kay Andersom, Alma I. Rodarte, and William E. Preston presented to the Gasification Technologies Conference, October 1998. It should be noted that Texaco's gasification business resides in the business unit Texaco Global Gas & Power.

We want to make it clear that this project did not have an FT unit. The economics resulted from the Texaco gasifier technology alone. However, the addition of an FT unit has some very interesting ramifications. In many parts of the world, excess electricity made by the gasifier may have no market outside the refinery due to either lack of demand or restricted access to the electrical grid. In these cases, an FT unit can prove valuable as syngas in excess of what is needed to make electricity to power the refinery can be diverted to make FT products. As long as the FT products fetch at least \$13 per barrel,<sup>38</sup> the addition of the FT plant will be economical. Given that FT products are environmentally superior to conventional refined products and should command a premium, even at today's depressed prices for refined products, we would expect FT products to sell at a \$5+ per barrel premium. At these levels, assuming an FT unit was added to the IGCC unit in the refinery of the type and size described in the previous paragraph, at an incremental cost for the FT unit of around \$100 million, revenues would increase some \$250,000 per day. We estimate an internal rate of return of around 20% on such a project.

Refiners are and always have been plagued with the problem of refinery bottoms and have spent billions of dollars on various solutions. Texaco's IGCC and Rentech's Fischer-Tropsch technology is just one more and possibly a better solution<sup>39</sup> in some circumstances and we expect some of those billions in the future to be spent on IGCC/FT plants.

## SOLIDS

Texaco's gasification equipment is also used to gasify coal and Rentech's FT process can effectively convert the syngas made from coal to FT products. Texaco has some 20 plants in China and one showcase plant in Florida owned by Tampa Electric Power & Light. We believe over time gasifying coal and producing both electricity and FT products therefrom has the potential to become a huge global business due to the very substantial reduction of carbon and other emissions that results.

Coal, as currently used in conventional coal-fired electricity plants, has the highest quotient of carbon pollution per energy content as discussed in the environmental section of this report. However, by utilizing a gasification technology like Texaco's and a FT technology like Rentech's, drastic reductions in carbon emissions can be realized. This conclusion was reached by the U.S. Department of Energy working with contractor Mitretek Systems.

The approach set forth by Mitretek is referred to as the "CoCo concept" which refers to the overall process of gasifying coal and natural gas together in a gasifier and then producing traditional electrical power from the syngas as well as FT products.

It is an interesting exercise to look at the effect this CoCo approach could have on U.S. carbon emissions. To do so, we must compare the carbon emissions currently produced from conventional coal fired plants with the emissions that would be generated if we converted all of that capacity to CoCo.

The U.S. Energy Information Administration in its 1998 Annual Energy Outlook estimated that in 1996 there were 1,797 billion kilowatt-hours of electricity generated in the U.S. and they went on to further estimate that 460.9 million metric tons (mmt) of carbon emissions were generated. We estimate that 440 mmt of the carbon emissions came from conventional coal-fired electrical generating plants. Given the lower carbon emissions of CoCo, we estimate that a reduction of 82 mmt per year of carbon emissions could be achieved and further, if all currently proposed new conventional coal-fired electrical generating plants were CoCo, another 13 mmt per year of carbon emissions reduction could be achieved.

<sup>38</sup> The approximate value of 42 gallons of heating oil on the New York Mercantile Exchange as of the date of this report.

<sup>39</sup> To be absolutely accurate, we should point out that Texaco can, under the terms of its agreement with Rentech, license Rentech's FT process to other companies with gasification technologies though, as pointed out, Texaco is by far the leader in the gasification field.

If we add these two categories of carbon emissions reduction together, we can project around 95 million metric tons per year in carbon emissions reduction which would achieve some 18% of the US's Kyoto target of 533 mmt carbon emissions reduction by the year 2010.

Taking the foregoing clean fuels theme a bit farther, if we assume bottoms in refineries around the world (both liquids like resid and solids like coke which, taken together constitute around 10% to 20% of current world refinery output) are gasified and turned into electricity and FT products, then we could process around 7 to 15 million barrels per day and reduce carbon emissions by some 39 to 77 million metric tons not to speak of the reduction in other noxious and troublesome emissions like nitrogen oxide (NO<sub>x</sub>), sulfur dioxide (SO<sub>2</sub>), and particulates.

It is beyond the scope of this report to conduct a study of the potential impact of Fischer-Tropsch on all forms of pollution around the world. Further, we have found in our conversations with FT technology companies, that while some have varying degrees of knowledge and appreciation of the positive benefits FT may hold for the environment, the "industry," like any nascent industry, has yet to evolve a full appreciation for its own potential, nor a coherent and unified industry message in this respect.

Further, due to the lack of an articulated position on the specific potential environmental benefits of FT at the current time and the lack of industry interface with policy makers, little is known or appreciated by policy makers about the environmentally positive aspects of Fischer-Tropsch technology. However, given the dramatic reductions that can be achieved in emissions of greenhouse gases (CO<sub>2</sub>) and acid rain (NO<sub>x</sub> and SO<sub>2</sub>) and other pollutants as we have hinted at herein, we believe that FT's promise or "prowess" in this respect may well be one of the primary drivers for near-term development of the technology—however, it is up to the industry to quantify the potential benefits of Fischer-Tropsch to the environment and get that message out to policy makers.

## FT PLAYERS AND PROJECTS

By our count, there are 14 Fischer-Tropsch plants that either have been announced or are under serious discussion. We estimate that the announced plants will produce about 120,000 barrels per day of FT products and if all projects are built, some 1,000,000 barrels per day of FT products would be manufactured.

Fischer-Tropsch projects have been announced or are in the discussion stage in all major areas of the world.

- North America – Alaska\* and Wyoming\*
- South America – Brazil\*
- Europe - UK North Sea† and Norwegian North Sea†
- Russia – Sakhalin†
- Africa – Nigeria\*†
- Middle East – Qatar†
- Asia/Pacific – Bintulu\*, Bangladesh\*, and India\*

Fischer-Tropsch projects have been announced or are in the discussion stage for both onshore\* and offshore† areas. Nine companies have some form of proprietary Fischer-Tropsch technology or are pursuing some research and development in the field:

- British Petroleum
- Conoco
- Exxon
- French Institut Francais du Petrole
- Rentech
- Royal Dutch/Shell
- Sasol
- Syntroleum
- Williams Company

Of the foregoing, only five companies can be considered "real players" at the current time in the sense that they have operated full-scale plants, pilot plants and/or signed agreements or are actively pursuing agreements to license or use their Fischer-Tropsch technology. These companies are Exxon, Rentech, Sasol, Shell, and Syntroleum.

In addition to the companies with their own proprietary Fischer-Tropsch technology, a number of companies have licensed Fischer-Tropsch technology or have announced that they will participate in Fischer-Tropsch projects. These companies are Arco, Chevron, Enron, Kerr-McGee, Marathon, Phillips, Statoil, Texaco, and YPF.

These players, and the partners they have taken on, have built, will, or may build the following FT plants.

### **FT PLANTS NO LONGER OPERATING**

#### **Shell Bintulu Plant**

12,500 barrel per day (bopd) plant converting around 100 million cubic feet per day (mmcf/d) of natural gas into about 1/2 middle distillates and 1/2 a combination of solvents, detergent feedstocks, and petroleum waxes. In part, sold middle distillates to Tosco as a refinery blending agent to make California CARB diesel fuel. Currently not producing due to an explosion December 25, 1997 in the air handling unit—not in the Fischer-Tropsch reactor. This plant is expected to be on-line again in 2000 with expanded capacity.

#### **Rentech Synhytech Plant**

This small plant was constructed by Public Service Company of Colorado to use landfill waste gas to produce 235 barrels per day of liquids. Located in Pueblo Colorado, production began in January 1992. However, the quantity of methane produced by the landfill proved insufficient to run the plant. Rentech assumed ownership of the plant and modified it to use pipeline-quality gas so that the technology could be proved and subsequently, in August of 1993, the plant was shut down.

### **EXISTING OPERATING PLANTS**

#### **Sasol One, Two, and Three plants**

Currently producing around 160,000 barrels per day of FT products from coal.

#### **South African Govt. "Moss gas" Plant**

This plant has been controversial since its inception and without continued government subsidy would likely have been shut down for economic reasons. Currently produces 23 thousand barrels per day (kbd).

#### **Exxon**

Exxon has a 200-barrel-a-day process-demonstration plant in Baton Rouge that has been operated for a number of years. (While this plant is not currently operating to the best of our knowledge, it could, and therefore we have included it in this category.)

## ANNOUNCED PLANTS

### Syntroleum "Sweetwater" Plant

In May 1997, Syntroleum formed Sweetwater LLC a company set up to design and construct an 8,000 barrel per day specialty product plant. Enron currently is to own 11% in consideration of a \$15 million capital investment. Construction is to begin in 1999 and operations in 2001.

### Syntroleum "Joint Venture GTL" Plant

SYNM, Texaco, and Brown & Root have begun a project to build a 2,500-bopd, possibly barge-mounted GTL plant.

### Syntroleum and ARCO

In October 1997, the companies announced plans to construct a 70-bopd pilot plant to demonstrate a slurry reactor at ARCO's Bellingham Washington Refinery. Expected start up is 1Q99. ARCO says it has 13 trillion feet of natural gas reserves on the North Slope of Alaska and while LNG is the current preferred solution, GTL is in the running.

### Rentech/ Donyi Polo Petrochemicals

The companies plan to refurbish the Pueblo Colorado plant and make industrial waxes. The 300-bopd plant is to be relocated to Arunachal Pradesh India. (Plant is in India now.)

## "POTENTIAL" PLANTS

### Shell Bangladesh Plant

Shell has plans to build a 50,000-bopd plant in Bangladesh that will use a "fourth-generation" process that will yield more middle-distillates and less wax.

### Sasol, Phillips, and Qatar General Petroleum Corp.

In July 1997, Phillips announced it signed an MOU with Sasol and QGPC for a feasibility study for a 20 kbd plant in Qatar to be located in Ras Laffan Industrial City. Scheduled start-up would be 2002. Sasol's share 34%, Phillips – 15%, and QGPC – 51%.

### Statoil/Sasol offshore Norway

The companies formed an alliance in April 1997 and plan a plant for operation in 2000. Project allows production of gas without having to lay pipelines.

### West of Shetlands Plant

Industry sources say the companies are considering a 500 million to 2 billion cubic feet per day (bcfd) plant for the Atlantic Margin West of Shetlands to produce 50 to 200 kbd of middle distillates. Partners are Texaco, Mobil, Shell, BP, Conoco, and Total. This plant is referred to as the "Aurora Project."

### Texaco, Petrobras, and Syntroleum

The companies are purportedly looking at GTL as a means of producing gas onshore Brazil in the Amazon Valley.

### Exxon - Qatar

Exxon is negotiating with QGPC to build and operate a 100 kbd plant in Qatar. While it has been reported that arrangements were to be finalized in 1Q98, per a recent conversation we had with Exxon, negotiations still continue.



#### **Exxon - Alaska**

As an alternative to an LNG plant, Exxon is studying a 200,000 barrel per day GTL plant for Alaska's North Slope. However, given the mix of gas owners (Exxon, ARCO, BP, and others) the horse race has already begun as to whose technology will be used. The LNG study group consists of BP, Exxon, ARCO, Yukon Pacific, Phillips, and the State of Alaska. The North Slope is estimated to contain 30-35 trillion cubic feet of natural gas.

#### **Syntroleum and ARCO - Alaska**

Studies have centered around a 200 kbd plant.

#### **Sasol and Chevron**

The companies completed a preliminary feasibility study in 1998 concerning GTL in Nigeria—20 to 30 kbd facility. The plan would be to site a plant adjacent to Chevron's Escravos gas project and crude oil export facilities in Nigeria in order to process gas currently flared in connection with crude oil production.

In addition to these players and projects, a number of other agreements have been struck evidencing that the Fischer-Tropsch "race to market" is on.

## **LICENSES AND AGREEMENTS**

#### **Syntroleum and Texaco**

In October of 1996, the companies announced two agreements: a nonexclusive Master License Agreement and a joint development agreement.

#### **Syntroleum and Marathon**

In March of 1997 the companies announced a nonexclusive Master License Agreement. In an internal Marathon memorandum drafted to help personnel explain this agreement, the company says in part "Marathon has a major stake in the Russian Far East, Sakhalin. This field complex has significant gas reserves and we are considering use there."

#### **Syntroleum and Bateman**

In April of 1997, Syntroleum announced it had entered into a project development agreement with Bateman to build a series of "natural gas refineries" in North and South America to produce synthetic lubricants, solvents, and chemical feedstocks.

#### **Syntroleum and ARCO**

In April of 1997, the companies signed a non-exclusive Master License Agreement for the Syntroleum Process®. The agreement provides ARCO with rights to use the process in broad geographic areas, including Alaska.

#### **Syntroleum and YPF**

In August of 1997, the companies announced they had entered into a nonexclusive license giving YPF the right to use the SYNM process in certain areas outside of the United States.

#### **Syntroleum and Kerr-McGee**

In February of 1998, the companies announced they signed a nonexclusive license giving KMG the right to use the SYNM process outside North America.

#### **Syntroleum and Enron**

In February of 1998, SYNM granted a non-exclusive volume license for the Syntroleum Process® outside of North America for the production of liquid fuels.

### **Syntroleum and Chrysler Corporation**

In October 1998, the companies announced an agreement to develop designer fuels derived from natural gas that will be sulfur-free, affordable and potentially cleaner than any transportation fuels currently available.

### **Rentech and Texaco**

In October of 1998, the companies announced they signed an agreement granting Texaco (1) an exclusive license to use for its own account, and sub-license, Rentech's FT technology with non-gaseous feedstocks and (2) a non-exclusive license to use for its own account, Rentech's FT technology with gaseous feedstocks.

Finally, two other situations bear mentioning with regard to the "deals" struck in the Fischer-Tropsch field:

- 1) Royal Dutch/Shell Group owns an indirect interest in Syntroleum through its 50% ownership of Criterion Catalyst, which in turn owns 3% of SYNM.
- 2) Marathon has a direct investment in Syntroleum of about 1% (paid \$1 million).

As this recitation of the various players involved in the Fischer-Tropsch field, as well as their level of activity indicates, the strategic positioning that is taking place with respect to FT is nothing sort of extraordinary and is a compelling indication of the potential of the technology.

## **R&D PROJECTS**

All companies with FT technology are constantly engaged in research and development to improve their processes. Among other things, these efforts include improving reactor designs and catalysts. While these efforts will no doubt lead to improvements in the costs of producing FT products as well as reductions in capital costs, these improvements can be thought of as incremental rather than step function. On the other hand, there are a few R&D efforts underway in the industry that may result in substantial cost breakthroughs and these are discussed in this section of this report.

Two projects are pursuing the use of ceramic membranes to separate oxygen from air. Oxygen (as we discussed earlier) is generally required in the first stage of the FT process, which is the manufacture of "syngas." Estimates are that the cost relating to the oxygen phase is 20-30% of the total FT cost and successful deployment of the ceramic membrane technology holds great promise to reduce this. The projects are:

### **The Oxygen Transport Membrane Alliance**

Sasol, Amoco, BP, Praxair, Statoil,

### **U.S. DOE Ceramic Membrane Project**

**\$84 million cost. Partners include Air Products plc, ARCO, Chevron, Statoil, and Babcock & Wilcox. This project is expected to have an 8-year life.**

As previously mentioned in the review of Fischer-Tropsch feedstocks, Rentech is also pursuing a project to eliminate the need for an oxygen-making unit in the syngas step. In August of 1998, Rentech announced an agreement with Thermal Conversion Corp. (TCC) to evaluate the use of the TCC plasma technology to convert natural gas into a tailored synthesis gas, suitable for use by Rentech's FT process. Recently, Rentech and TCC announced that phase I of the testing which consisted of computer modeling of the process was successful and the companies plan to move to phase II which is a physical testing of the

process. This testing should be completed in the first quarter of 1999. If the "plasma reforming" process is successful it will eliminate the oxygen plant and CO<sub>2</sub> removal although the process appears to be applicable in small FT plants only.

Perhaps the most profound technology currently being pursued is a project to develop single step catalytic conversion of **natural gas** to liquid fuels such as methanol and gasoline (rather than the current two step process of (1) making syngas and (2) reacting the syngas in the FT reactor to make FT products). The partners in this venture, which is a 3-year program, are Catalytica, Syntroleum, Petro-Canada, and Mitsubishi.

Catalytica describes the process as follows:

Catalytica Advanced Technologies is developing a new class of catalysts for the direct oxidation of methane into methanol or other liquid hydrocarbons - a process which could be complementary to and potentially less expensive than some current Fischer-Tropsch technologies.

Under the terms of Syntroleum's agreement with Catalytica, Syntroleum has exclusive rights to market the technology worldwide.

Should any one or more of these new technologies prove effective, the economics of Fischer-Tropsch products could be dramatically improved leading to more rapid market acceptance of the process.

## COMPETING TECHNOLOGIES

Any discussion of Fischer-Tropsch would be incomplete without considering alternative means of monetizing natural gas. However, we will spend less time in this subject area than some other reports on Fischer-Tropsch for two reasons. First, our purview is not limited to natural gas as a feedstock. Second, as will be seen, we view the alternative approaches as rather limited.

There are essentially four other routes to monetize stranded natural gas:

- *Convert the gas to methanol*
- *Convert the gas to ammonia*
- *Liquefy the natural gas*
- *Build pipelines*

The first two options are severely limited by the small markets for the end products. Per Houston-based CMAI's annual World Methanol Analysis for 1998, current supply and demand are fairly well balanced at around 26 million metric tons.

CMAI says over the next 5 years, twice as much supply growth (6 mmt) is projected as demand growth. Further, that total supply growth will use up only around 135 million cubic feet per day of natural gas. If you refer to the table of the world's gas fields that we presented earlier, you will see that all of that methanol growth would use up only one of the world's 327 estimated gas fields with over 1 trillion cubic feet of reserves.

In short, comparing the economics of methanol and GTL is largely an academic exercise as there is just no way methanol demand will possibly use up any appreciable portion of the world's stranded gas reserves in any of our lifetimes. The same is true of ammonia. While the ammonia market is about five times

as large as the methanol market, if we default to the methanol growth figures<sup>40</sup>, only five more 1 tcf+ stranded gas fields of the world's 327 estimated gas fields with over 1 trillion cubic feet of reserves could be monetized by converting the gas to ammonia.

Moreover, in thinking about Fischer-Tropsch as an approach to monetizing stranded gas versus making ammonia or methanol, one must keep in mind that ammonia and methanol are discrete products with discrete end uses<sup>41</sup>. Even assuming robust growth rates for these end products, they can not make more than a small dent in monetizing the world's 2500 tcf of stranded gas reserves. For instance, Syntroleum notes in some of its publications that on a oil equivalent basis, the world uses 280 thousand barrels per day of methanol, 780,000 barrels per day of ammonia and around 36 million barrels per day of middle distillates!

What about liquefied natural gas or LNG, as it is called? The first thing to realize about LNG is that it is not a process for converting natural gas to something else. It is in reality nothing more than a transportation mechanism for natural gas. In LNG, you start with natural gas, you liquefy it for transport and then "un-liquefy" it for use (i.e., vaporize it). It is an alternative to either building a pipeline or leaving the gas in the ground. LNG currently accounts for about 4% of world natural gas supply.

The second thing to realize about LNG is its scale. The capital investment ranges from \$3 to \$5 billion and the minimum natural gas resource must be around 5 to 7 trillion cubic feet. Given these parameters, as Joe Verghese, VP of Oil and Gas Technology for ABB Lums Global noted in a paper entitled "State of the Art in GTL Technology" given in London in November of 1998, "In view of the fixed cost incurred in the LNG supply chain, a key market characteristic of LNG development projects has been the linkage with secure long-term off take destinations. These arrangements are underpinned with sale and purchase contracts for 20-25 years prior to the launch of an LNG project."

In short, LNG projects are big, capital intensive, and require long-term commitments and monstrous gas fields<sup>42</sup> of which, again referring to the table of stranded gas fields, there are less than 100 around the world leaving the remaining fields for FT development.

Finally, with respect to natural gas, building a pipeline is clearly a competitive option though most writers on this subject essentially disregard this option as they start out defining the problem as "stranded gas" which by definition, is not accessible by pipeline. We do not want to approach the subject exactly the same way as there are some discrete projects around the world where a pipeline is a distinct possibility as an alternative to FT and further, some markets in general, like the Southern Cone of South America which currently has significant stranded gas reserves, may well develop those reserves through pipelines in a 10-year time frame.

With regard to specific projects, the 35 tcf on Alaska's North Slope and the associated gas at Sakhalin Island are both being studied currently with an eye towards pipelines as a possible solution. Natural gas pipelines are also under study to unlock stranded gas in the Caspian region. One route proposed by Unocal goes through Turkmenistan and Afghanistan and another route proposed by Exxon goes all the way across China! Obviously, pipeline projects like these are huge capital investments and as fixed installations, political stability in host countries is of paramount concern.

<sup>40</sup> Which we believe is a reasonable alternative in the interest of brevity and especially, as you will see, in consideration of the relative insignificance of ammonia in monetizing the world's stranded gas fields.

<sup>41</sup> Primary markets for ammonia are fertilizer and industrial chemicals; methanol's are formaldehyde, MTBE, and acetic acid.

<sup>42</sup> In the spirit of full disclosure, we should note that Mobil has been progressing a technology for a smaller LNG plant design that might be deployed on a mobile basis offshore. However, to date, this design has not been tried or tested in the field.

With respect to the economic comparisons of the competing technologies, we hope we have made it clear that we do not view an economic comparison of methanol and ammonia plants to be particularly germane to whether and when FT projects will come to fruition. As to LNG versus GTL, two noted investment firms have made economic comparisons<sup>43</sup> and both concluded that investment returns on both technologies are roughly comparable. One author gave the nod slightly to LNG, the other, slightly to GTL (at the high point of his comparison range).

As to industry comments on the subject, Dr. Benjamin Eisenberg, Technical Project Manager of Gas Ventures for Exxon noted at a meeting on GTL sponsored by Bloomberg Financial Markets, October 29, 1997, that Exxon considered the economics of LNG and GTL to be equal. Further, in a multi-client study conducted by A.D. Little, which included Exxon, Shell, and Sasol, one of ADL's conclusions was that "GTL technology is broadly competitive with LNG and/or pipeline gas." We believe it is also very important to realize that regardless of whether the economics of LNG and GTL are equal or approximately equal, LNG does not and cannot make the same end products that GTL does. In fact, LNG does not make products at all, it is merely a distribution system for natural gas. It is in the vast refined products markets and to some extent, petrochemicals markets that FT fits in. In this respect, LNG is no competition.

As to the economics of pipelines as a competing technology, other than the previous ADL comment, we are not going to try to quantify the matter. Pipeline costs will be virtually completely project specific and vary based on length, topography, both above water and below water, local and regional risks of natural disasters such as earthquakes, local environmental regulations, risk of terrorist activity, etc. Having said that, clearly, the fundamental thrust of GTL is to move the energy in natural gas from areas of sparse population or areas of very low energy usage to areas of energy usage intensity; from the Middle East to Europe or the U.S., for instance.

With regard to the competitive aspects of FT as applied to solids and liquids, we have already commented on the potential economics benefits of a gasifier deployed in a refinery setting and believe that Texaco's decision to license FT technology as an add-on to its global gasifier business reflects Texaco's belief that it will be successful in finding customers for combined gasification/FT units. As to FT as applied to coal, an economic study performed by SFA Pacific indicates that in the U.S., oil prices in the high \$20 per barrel range will be required to induce such projects to go ahead in the absence of "stick"-type legislation requiring coal users to adopt the technology and/or "carrot"-type legislation providing tax credits for its adoption (some version of the Section 29 tax credit for instance which had a profound impact in spurring drilling for coal seam gas).

Finally, with respect to the competitiveness of Fischer-Tropsch, we believe that the pace at which the technology is adopted will be very much influenced by the extent to which capital costs are reduced. We mentioned earlier a paper given by Mr. Verghese at a recent symposium on FT and in that paper the author makes an interesting observation worth restating at this juncture. He says "Over the past 20 years, there have been impressive technology advances in LNG plant configuration, resulting in some 50% reduction in the cost of liquefaction units compared to the costs of units in the 1960s/early 1970s." Echoing that basic thought, though without quantification, Exxon says "...the learning curves characteristic of new refining technology should be applicable to the AGC-21 pioneer plants for capacity and yield..."<sup>44</sup>

One could say that the "acid test" for comparing FT in terms of economic competitiveness—the ultimate benchmark—is the capital cost of building a refinery which is pegged in a range of \$12,000 to

<sup>43</sup> Monthly Energy Perspectives—September 1997 "Answering the Gas To Liquids Question," by Doug Terreson of Morgan Stanley Dean Witter, September 9, 1997 and a report on Syntroleum Corporation dated October 27, 1998 by Paul Ting of Salomon Smith Barney.

<sup>44</sup> From a paper presented at the Alternate Energy '94 meeting, April 26-29, 1994 in La Quinta, California entitled "Liquid Fuels from Natural Gas—An Update of the Exxon Process" by L.L. Asell, B. Eisenberg, R.F. Bauman, and G.R. Say, all of Exxon.

\$14,000 per daily barrel.<sup>45</sup> If FT technology breaks through to this level, "natural gas refineries," will become compelling alternatives for producing refined products, especially given the fact that as Dale Simbeck of SFA Pacific notes in discussing the environmental benefits of natural gas, "natural gas is the big fuel mix' winner."<sup>46</sup>

Can FT make this breakthrough? A number of studies peg the cost of the various existing FT technologies in a \$20,000 to \$30,000 per daily barrel range. If FT technology capital cost mirrors the LNG example given earlier, the answer would seem to be yes. On the other hand, a distinction with regard to the comparison between LNG and FT must be made. Twenty years ago, LNG technology was essentially brand new. FT has been around since the 1920s. Further, the syngas step is an old technology. As noted, Texaco began the development of its business 50 years ago. On the other hand, very few modern FT plants have actually been built and even fewer have been operated more than several years. So, the cost reduction curve probably lies somewhere below the 50% LNG experience but, may still be substantial. Further, according to Syntroleum, the promise of breakthroughs in eliminating the oxygen step and yet getting the process benefits of POX or ATR are possible. Also, plasma reforming bears some attention considering that this breakthrough may be achieved, at least on a pilot plant basis, within a few months.<sup>47</sup>

Another observation is apropos. Syntroleum's license agreements require all licensees to share any and all technological improvements to the Syntroleum Process® both in the R&D phase (so-called "grantback" provisions) as well as in the plant construction and operation phase. In this manner, the pace of technological advancement should be accelerated due to "cross-pollination" as more and more minds focus on improving the technology and share those improvements with each other.

But does the FT industry really have to achieve refinery capital cost levels to become a mainstream technology. Ben Eisenberg of Exxon says no. He notes that the economics of FT have to include the economics of the resource base. The ultimate question is: what will be the rate of return on an investment to find, produce, transport, refine, and market hydrocarbons? The decision tree then starts to have branches such as the following: should I pursue new deepwater exploration in West Africa or new oil reserves in the Caspian Sea or should I install production facilities at already discovered stranded natural gas reserves (such as those in Alaska) and build a GTL plant?

## PATENTS AND PATENT ISSUES

This is a prickly issue, which, none-the-less, is one we must tackle. Patents covering Fischer-Tropsch and related processes abound. In fact, by the 1950s, over 4,000 patents relating to FT catalysts had been issued. Exxon is "king" with some 400 United States patents and around 1,500 patents worldwide. Syntroleum "owns or has licensed rights to over 43 patents and patent applications."<sup>48</sup> Rentech has 9 patents and additional patents pending.

According to Rocco A. Fiato, Senior Engineering Associate with Exxon, Exxon has been involved in numerous patent interference actions with several companies including Shell—14 times in Europe over patent issues relating to FT in which Exxon prevailed 14 times. Exxon has also brought a suit, filed March 26, 1998, against the United States of America in the United States Court of Federal Appeals. Exxon alleges

<sup>45</sup> This formula would mean that the capital cost range for a refinery that refines 100,000 barrels per day of crude oil would be \$1.2 billion to \$1.4 billion.

<sup>46</sup> From a paper entitled "Gasification in a Carbon Constrained World" presented at the 1998 Gasification Technologies Conference, October 4-7, 1998.

<sup>47</sup> It should be noted that plasma reforming uses a lot of electricity which will have to be taken into consideration in calculating the overall economics of using the process in any particular FT application.

<sup>48</sup> Per the company's Joint Proxy Statement with SLH Corporation relating to the two companies' recent merger.

in this suit that the U.S., "through its Department of Energy...and DOE's authorized contractors and subcontractors, has used Exxon's patented [AGC-21] technology to make liquid hydrocarbons and further the economic interests of Exxon's competitors."

In summary, the background of this suit is that the DOE has an FT research facility at La Porte, Texas and DOE authorized Shell Synthetic Fuels, Inc., an operating unit of the Royal Dutch/Shell Group of Companies and Air Products and Chemicals, Inc., and others to "engage in gas-to-liquids conversion...using processes and techniques patented by Exxon."

The two specific patents Exxon alleges were infringed were patent No. 5,348,982 entitled "Slurry Bubble Column" and patent No. 5,292,705 entitled "Activation of Hydrocarbon Synthesis Catalyst." Exxon also says in the suit that perhaps more of its patents were infringed.

While Exxon will not generally comment on the specifics of pending legal actions, what we have been able to discern by talking to various industry players is that Exxon is seeking to protect its rights to its cobalt catalyst used in a slurry reactor.

While we have not been able to confirm this with Exxon, what we have been told by others in the FT field is that Exxon originally filed patent applications in Europe covering use of a slurry reactor and both cobalt and iron catalysts. While Exxon was granted the patents with respect to cobalt and the slurry reactor, it was denied the patent with respect to an iron catalyst and a slurry reactor. Further, when Exxon filed its patents in the United States, it did not receive patent protection on the use of an iron catalyst in a slurry reactor.

It should be noted that Rentech and Sasol have employed an iron catalyst in a slurry reactor and to our knowledge, have not been sued by Exxon, nor has Exxon otherwise objected to their deployment of this technology.

While the extensive discussion earlier of FT reactors and catalysts may have seemed rather dry and academic, it was presented in part so that the reader could understand the stakes with regard to these patent infringement issues.

Cobalt catalysts offer certain advantages over iron and slurry reactor design offers some advantages as well over other FT reactor designs (as previously discussed). It is not our purpose here to argue which of these is better, but it is clear from the descriptions of the various companies' technologies that both Shell and Syntroleum are pursuing the deployment of cobalt catalyst in a slurry reactor, though, as mentioned earlier, Syntroleum is developing with Texaco its "HMX" reactor, a non-slurry reactor, which it believes will be the preferred design going forward.

Also, Syntroleum and three of its licensees have done thorough reviews of all of what they believe are the relevant Fischer-Tropsch-related patents. These reviews have been conducted not only by the companies' internal counsel but also by outside patent counsel retained by Syntroleum and three of its licensees. Based upon these exhaustive reviews, Syntroleum and its licensees do not believe they have or will infringe on any one's patents.

We do not know how narrow or broad Exxon's issues are with regard to its contention of patent infringement and further, we have not attempted to analyze the merits of the "La Porte" suit or the validity of the patents involved and therefore, we have no idea if some or all of Exxon's patents will ultimately provide Exxon protection if adjudicated in a court of law. However, we do believe it important for investors to be aware of this legal action with regard to patents.

# STRATEGIC IMPLICATIONS OF FISCHER-TROPSCH

## OVERVIEW

We believe the strategic implications of the deployment of Fischer-Tropsch are immense. We believe it has the potential to substantially rearrange the playing field for companies involved in producing and refining energy sources. Further, we believe it has the potential to dramatically reduce carbon emissions and emissions of other problem compounds like NOx and SOx.

These conclusions are based on certain "global" observations:

- There are huge untapped reserves of natural gas around the world.
- The energy in coal reserves exceeds that of oil and natural gas.
- The world is deregulating its electricity grid.
- Crude oil is getting heavier and more sour.
- The competition for access to oil and gas reserves is intense and getting more so.
- Returns on refining investments are low and competition is intense to improve them.
- Pressure to reduce harmful emissions is mounting.
- The intensity of world energy use is growing.
- The world population is growing.

Further, Fischer-Tropsch cuts across the functional boundaries<sup>49</sup> of the oil and gas industry and has the potential to impact the way we use coal as well. Fischer-Tropsch can:

- Produce synthetic oil to compete with conventional oil.
- Unlock the potential of stranded gas.
- Unlock the potential of substandard gas.
- Solve the problem posed by restrictions on flaring.
- Unlock oil production where gas also has to be produced.
- "Bust the bottoms" in a refinery.
- Produce electricity and FT products from coal while dramatically reducing emissions.
- Produce high value, high quality refined products for today's markets.
- Produce higher purity refined products to meet tomorrow's higher environmental standards.
- Provide a bargaining chip for companies to attain equity positions in already found reserves.
- Enhance and maximize the value of already built infrastructure.

Another "global" observation that emerges in consideration of the fact that the potential impact of FT cuts across functional boundaries is that the major integrated oil companies are clearly in the best position to exploit the technology. We will return to that thought after reviewing the various companies that have FT technology and what they plan to do with it.

<sup>49</sup> The "upstream" which explores for and produces oil and natural gas, the "midstream" which transports oil and natural gas, and the "downstream" which turns hydrocarbons into usable end products like gasoline and diesel.



## REVIEW OF FT PLAYERS & STRATEGIES

Two global integrated major oil companies, Exxon and Royal Dutch have FT technology. Sasol, an essentially downstream company has FT. Exxon has specifically said it does not intend to license its technology and seems very resolute to protect it. Shell and Sasol also appear unlikely to license their technology.

Two upstart technology companies, Rentech and Syntroleum, have the technology. Syntroleum clearly has broadly licensed its technology and further, is keen to develop its own "natural gas refineries" for specialty products. Rentech has hitched its star to the Texaco "star" in the solids and liquids side of the FT business and while it may take equity interests in GTL plants, is more interested in gas-to-liquids licensing agreements.

Texaco has a key component of the technology, gasification, and licenses with both Rentech and Syntroleum (and the ability to sublicense Rentech's solids or liquids technology). While not directly related to FT, Texaco has entered into a worldwide agreement with Exxon for Texaco's gasifier technology and currently is engineering units in three of Exxon's biggest refineries on three different continents with interesting potential for retrofitting an FT unit.

While BP and Conoco have some sort of R&D effort under way, both would seem to be years behind Exxon and Shell<sup>50</sup>. Chevron, Phillips, and Statoil have announced ventures with Sasol. Texaco, Arco, Enron, Marathon, YPF, and Kerr-McGee have announced licensing the technology from Syntroleum.

From this review, six distinct strategies emerge:

- 1) Use the technology for one's own account only (Exxon, Shell, Sasol).
- 2) Earn licensing fees from the technology and use the technology for one's own account (Syntroleum and to some extent, Rentech).
- 3) License other's technology for sublicensing (Texaco).
- 4) Develop the technology (BP and Conoco).
- 5) License technology (the rest mentioned).
- 6) Do nothing (everyone not mentioned).

## RENTECH AND SYNTROLEUM

One of the strategic implications of the foregoing should be obvious. No one likes to negotiate with just one party. So, everyone in the world that wishes to license the technology currently appears to have only two choices: Rentech or Syntroleum, Syntroleum or Rentech. While Rentech's technology has only recently been "vetted" by Texaco, and therefore (until October of 1998 when the Texaco "Deal" was signed) there was only one company, Syntroleum, from which one could license FT, now it's a "two-horse race" and we suspect that Rentech's activity level will pick up dramatically though given the extensive number of licenses Syntroleum has already signed and strategic relationships it has formed with engineering and construction companies as well as Chrysler, clearly, Rentech is "running from behind."

On the other hand, as Rentech would not seem to be faced with the potential patent problem we spoke of in the last section, it may be perceived as a "safer" bet by some though we note that given the long list of very large companies allied with Syntroleum and intent on using Syntroleum's FT technology, Exxon may have to take on the whole industry.

<sup>50</sup>Based upon conversations we have had with various FT technology company senior management as well as comments made by FT technologists at various industry meetings, we believe it would take around 10 years to develop an in-house FT capability "from scratch."

Another strategic implication with respect to licensing is that companies may well decide to license both technologies<sup>51</sup>. Given the financial resources of the world's large oil companies, this may be the safest ticket to the "party." A number of very large companies are absent from the scene at this point: Total, Elf, ENI, Repsol, the Russian "majors," as well as state oil companies like Aramco, Pertamina, PDVSA, Petrobras, etc.

As the number of licensing agreements entered into by Rentech and Syntroleum rise, the very real possibility that they may become takeover targets also rises and the potential for an alliance between the two, or an outright merger or sale is not out of the question either.

## UPSTREAM

Oil companies are engaged in virtually a death struggle to obtain access to oil and gas reserves. Unlike other industries, oil companies must in effect, reinvent themselves every decade or so as the oil and gas they found in the previous decade is produced. In other words, they must find oil and gas that can be produced—or die. This struggle is always difficult but it is especially difficult in the low oil price environment of today.

In addition to the issue of current low oil prices, other macroeconomic trends are making the struggle more difficult. Much of the oil that is easy and cheap to find has been found. Increasingly, oil companies have to explore in technologically challenging environments like the deepwater or in politically unstable locations like the FSU countries. Also, oil and gas companies have increasingly ended up finding natural gas in remote locations where there are no markets even though they were looking for oil.

The BP/Amoco merger clearly heralded the dawning of the era of "super-majors"; companies with massive size and financial wherewithal that can afford to make huge investments with very long lead times prior to positive cash flow and earnings. Exxon/Mobil ups the ante even more. These companies are very well suited to implement Fischer-Tropsch projects now, despite oil prices, as a means of acquiring an equity position in gas (and possibly oil) reserves.

For instance, it has been reported that Exxon has been negotiating with Qatar for years about building a 50,000-100,000 barrel per day GTL plant in that country. Qatar has some 300 trillion cubic feet of natural gas and nominal current production, relatively speaking. Recently, Saudi Arabia also indicated it was interested in receiving GTL proposals from the major oil companies. We understand that both Exxon and Texaco have studied such projects and may be in discussion with the Saudis. (Saudi Arabia is estimated to have 190 trillion cubic feet of natural gas reserves.)

For the major oils, the gas reserves of these two countries (and others) are tempting targets and FT may be the key to unlocking them. We believe the majors, Exxon, Royal Dutch, and Texaco will use FT as a bargaining chip to obtain an equity interest in such reserves. However, clearly, the owners of the gas may not wish to trade away their asset and may turn to Rentech and Syntroleum and license the technology directly. So another high stakes poker game may develop between the major oils with FT technology and the upstart technology companies. This raises the specter that Exxon or Shell decide it is better to buy out Rentech or Syntroleum, or both, rather than have to compete against them. If such an offer were to come in, other major oils might decide they better get the technology before Exxon or Shell buys it because if Rentech and Syntroleum are gone, from whom would they be able to license the technology?

An aside to this sort of strategic thinking is the positioning that may be going on between countries. Saudi Arabia has enough problems competing with its neighbors with large existing oil reserves (Iran, Iraq, and Kuwait). The last thing it needs is another substantial competitor, which Qatar could become if it signs a series of GTL deals (and it has already signed one with Sasol). We know from discussions with industry

<sup>51</sup> For instance, Texaco has licensed both Rentech and Syntroleum's technology—Rentech's exclusively for liquids and solids to liquids and non-exclusively for GTL; Syntroleum's, non-exclusively for all applications.

players that this point is not lost on the Saudis. While it is beyond the scope of this report to get into a discussion of OPEC strategy or the strategies of individual countries within OPEC with regard to oil supply and oil prices, one comment that was made to us by a senior executive at a major oil company is so salient that we would be remiss in not including it herein. The gist of that comment is that the single greatest threat that the Saudis see with respect to the primacy of oil is gas-to-liquids.

As Daniel Yergin's book The Prize makes clear, the politics of oil are a high-stakes game. We believe Fischer-Tropsch technology holds the promise to make the politics of natural gas the same.

To put a more concrete face on the upstream impact that FT could have on oil companies, consider the following. Syntroleum commissioned Arthur Andersen to calculate the effect a Syntroleum GTL plant could have on an oil and gas company's earnings. Based on the Andersen conclusions, Syntroleum calculated that by unlocking enough stranded gas to make 100,000 barrels per day of FT products (15 tcf), a company of a like size to Texaco, for instance, could increase earnings per share by 26% and price per share a like amount, assuming the company's PE multiple remained constant. Further, this effect resulted only from reducing Depreciation, Depletion and Amortization on a per barrel basis as the DD&A pool is spread over a larger reserve base. Additional economic benefits obviously could accrue from the operation of the FT plant.

Summing all of this up, major oil companies that have FT technology or have licensed it are advantaged in unlocking the value of stranded gas reserves they have already discovered as well as leveraging themselves into new reserves. Companies that do not have access to the technology are disadvantaged.

## MIDSTREAM & DOWNSTREAM

Fischer-Tropsch makes hydrocarbon products—pure and simple. Integrated oil companies are uniquely positioned to benefit in this respect. As this report has unfortunately probably made all too clear, refining and petrochemicals are complex and interwoven businesses that can best be optimized under "one roof" or within one integrated scheme. Integrated oil companies can best manage the carbon molecules in oil and gas from start to finish. Lee Raymond, chairman, CEO, and president of Exxon Corporation made this point clearly in discussing the decisions of Exxon's and Mobil's boards to merge the two companies. He said that the companies are in the business of "molecule management."

The application of FT in a refinery has the potential to substantially enhance refinery economics. Refiners should be able to:

- *generate all of their own power needs*
- *sell excess electrical power*
- *produce a cleaner slate of fuels*
- *run a heavier and cheaper slate of crude oil, and*
- *maximize the value of refinery bottoms*

While individual refineries may benefit from FT in the ways itemized above, looking at the effect on an industry basis, it should be clear that the consumer will be the real winner. In effect FT will constitute another technological innovation which will reduce the costs of making refined products and that cost reduction will get passed on to the consumer. Ultimately, we are not sanguine that returns in the refining business will get any better but we believe refiners will be forced to adopt the technology in order to stay competitive. Obviously, Texaco and Rentech are uniquely positioned to take advantage of this fact.

Finally, with respect to the midstream, since FT synfuel can use the same midstream infrastructure as oil, investments in existing pipelines and tankers can be maximized. This is an important consideration that is not normally quantified or even considered in simplistic comparisons of LNG projects versus FT projects.

## SUMMARY AND CONCLUSIONS

The adoption of Fischer-Tropsch technology has the potential to profoundly affect the oil and gas business as well as the world we live in. FT has the potential to:

- Increase the use of cleaner sources of energy like natural gas.
- Unlock stranded gas resources.
- Unlock oil resources that would otherwise not be produced unless associated gas is produced.
- Increase exploitation of heavy oil reserves.
- Substantially increase the booked reserves of oil companies around the world.
- Allow the continued use of "dirty" energy sources like coal and refinery bottoms in a more environmentally "friendly" way.
- Change the mix of uses energy sources are put to; for instance, making liquid transportation fuels from natural gas, refinery bottoms, and coal.
- Reduce the costs to consumers of conventional refined products by allowing refiners to use a heavier and therefore cheaper refinery crude slate as well as produce their own refinery electrical needs and sell excess power to the "grid"; i.e., deliver on the promise of the "bottomless refinery" as Texaco calls it.
- Allow for population growth and increases in energy usage intensity which are inevitable while providing a means of economically reducing harmful emissions.

Given the impact that Fischer-Tropsch technologies may have it should come as no surprise that competition is likely to be intense and brutal. Exxon's predilection for litigation is one indicia. The level of licensing Syntroleum's technology by companies that do not have their own in-house FT technology is another. Texaco's licensing both Rentech and Syntroleum's technology is a third.

Major oil companies have for years pursued strategies for accessing oil and gas reserves as well as strategies for refining the world oil slate which as mentioned, has been and will continue to get heavier and more sour. A new technology that has the potential to upset these strategies (not to speak of potentially obsoleting billions of dollars of investments) may be perceived by some as more of a threat than an opportunity.

The rate at which Fischer-Tropsch technology is adopted will be affected not only by the opportunities it creates but also by the extent to which it is perceived as posing a threat or threats. While it is impossible to accurately evaluate all of these factors, we can make some educated guesses and perhaps rank order which kinds of projects are likely to come to fruition first.

We believe oil projects that require the production of associated gas are one of the most-likely types of projects for near-term development; offshore West Africa and Sakhalin Island are examples. As previously noted, the cost to re-inject natural gas for these projects may be equivalent to \$3.00 per barrel. Syntroleum believes its FT process is economical at a \$15 per barrel oil price therefore, even at world oil prices of \$12 per barrel, these types of projects may work.

Flaring of natural gas in certain West African countries is generally prohibited for new oil projects and must be phased out over the next several years for existing production which we believe will accelerate the adoption of FT in these countries.

Some specific FT projects have been announced and we believe these will move ahead including: Syntroleum's Sweetwater plant, Rentech's Indian plant, and Shell's rebuilding of its Bintulu plant as well as its new 50,000 barrel per day Bangladesh plant.

We believe Texaco will move ahead quickly to build a pilot facility incorporating Rentech's FT process with its (Texaco's) gasification technology in a refinery setting. We believe after successful testing, within the next few years, Texaco will begin to deploy these combined gasification/FT plants in refineries around the world. It should be noted that the economics of these projects are largely unaffected by world oil prices.

The potential for a breakthrough in lowering the capital cost of building an FT plant is very real as discussed earlier in this report. Should this happen, the widespread adoption of FT projects may be substantially accelerated. Likewise, if the FT industry is successful in quantifying the potential environmental benefits FT technology offers and successful in "selling" those benefits to policy makers, an acceleration of the adoption of the technology could ensue.

In short, as was the case in 1975 with the personal computer, it is difficult to look forward 5, 10, or 20 years with respect to the potential impact of Fischer-Tropsch technology and see clearly what will happen. What we hope we have accomplished in this report, is to set forth the overall promise of Fischer-Tropsch technology.

## INVESTMENT OPPORTUNITIES

As all of the foregoing indicates, over the last few years, there has been an impressive level of activity on the FT front as the technology seems to be inexorably marching towards commercialization. Moreover, there are compelling reasons for Fischer-Tropsch to find commercial applications as we hope we have demonstrated in this report. So what are the investment opportunities?

In 1997, the only two "pure" plays in FT had quite a performance.

- SLH Corporation, NASDAQ ticker symbol "SLHO," the predecessor company of Syntroleum, NASDAQ ticker symbol "SYNM," climbed 457%.
- Rentech Inc., NASDAQ ticker symbol "RNTK," increased 875%.

But so far in 1998, the picture has changed dramatically. Both SYNM and RNTK have suffered dramatic declines.

### So what's changed?

The answer is the price of oil. The NYMEX near month oil contract which reflects the main U.S. benchmark oil price, West Texas Intermediate, peaked in 1997 at \$26.74 per barrel and averaged \$20.63. In 1998, the contract has averaged under \$15 per barrel. Our forecast is WTI prices in the \$14-\$16 range between now and year-end 2000 with a return to the \$18 mean in 2001 and beyond. (See Appendix I.)

Despite our conclusions as set forth in the previous section that many FT projects will move ahead in the near future and that oil prices are not the only determining factor, oil prices do play a part and it would appear that investors are most focused on this factor.

Accordingly, taking a short-term look, we believe that the 1997 FT investment momentum is momentarily stalled but will start to pick up again in 1999 when the visibility of improvements in the price of oil start to become apparent. At the same time, we would point out that both Rentech and Syntroleum have the potential to be event driven stocks. Should either announce technological breakthroughs or impactful projects, their stock prices could be positively affected. Moreover, we believe both stocks are substantially undervalued.

At their respective highs in 1998, RNTK reached \$3.34 per share and SYNM was \$19 per share. At \$19 per share, Syntroleum's total market capitalization is around \$500 million. Even at this level, Syntroleum's market value is less than 2/3rds of the equity value of the company as determined by the company's financial advisor in the July 1998 Joint Proxy Statement with SLH Corporation relating to the companies' merger.

As to Rentech, at \$3.34 per each of the company's currently outstanding 42 million shares (fully diluted), the company's market capitalization is only \$140 million.

Based upon the valuation work we have done, which includes an assessment of the potential value of recent licenses and agreements signed by both companies, we believe a fair valuation for both companies is well in excess of that implied by their 1998 per share highs, not to speak of their value based upon their current share prices.

Over the longer term however, we would hasten to add that the ability of Rentech and Syntroleum to make the transition from start-up technology companies to operating entities with substantial revenues and profits is far from assured. We believe competition in the Fischer-Tropsch field will be intense and brutal as we discussed in the "Strategic Implications" section of this report. Rentech and Syntroleum face daunting challenges, both endogenous and exogenous, in meeting that competition successfully.

## APPENDIX I: CRUDE OIL PRICES

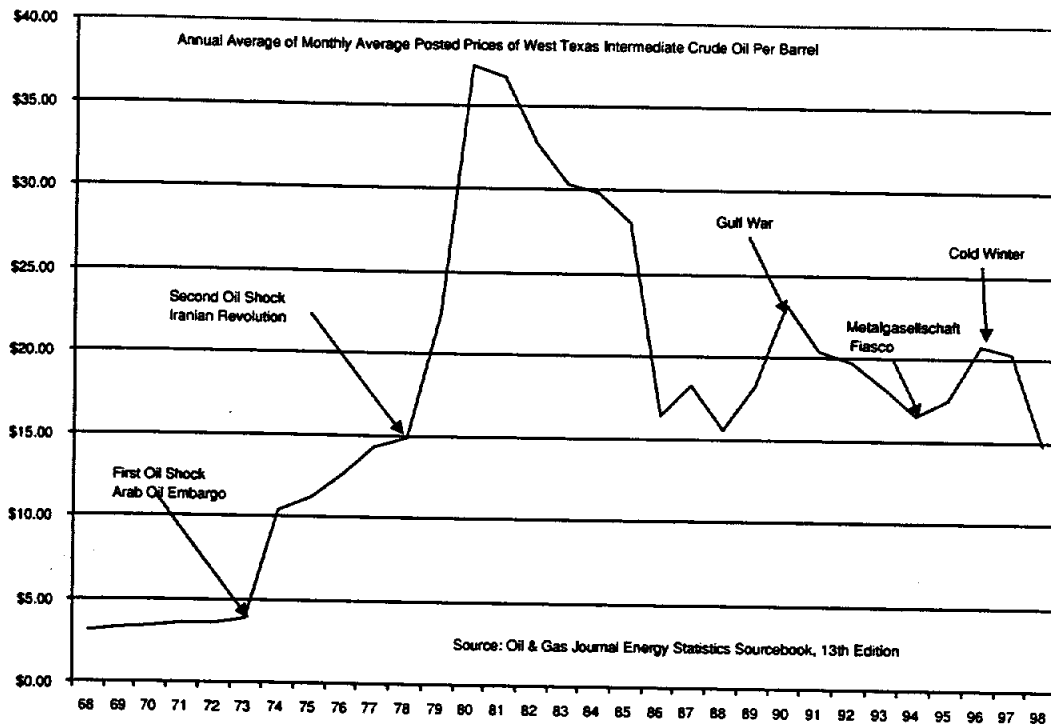
The NYMEX near month oil contract which reflects the main U.S. benchmark oil price, West Texas Intermediate, peaked in 1997 at \$26.74 per barrel and averaged \$20.63. In 1998, the contract has averaged well under \$15 per barrel.

The dramatic decline in the price of oil in 1998 is generally attributed to four main factors:

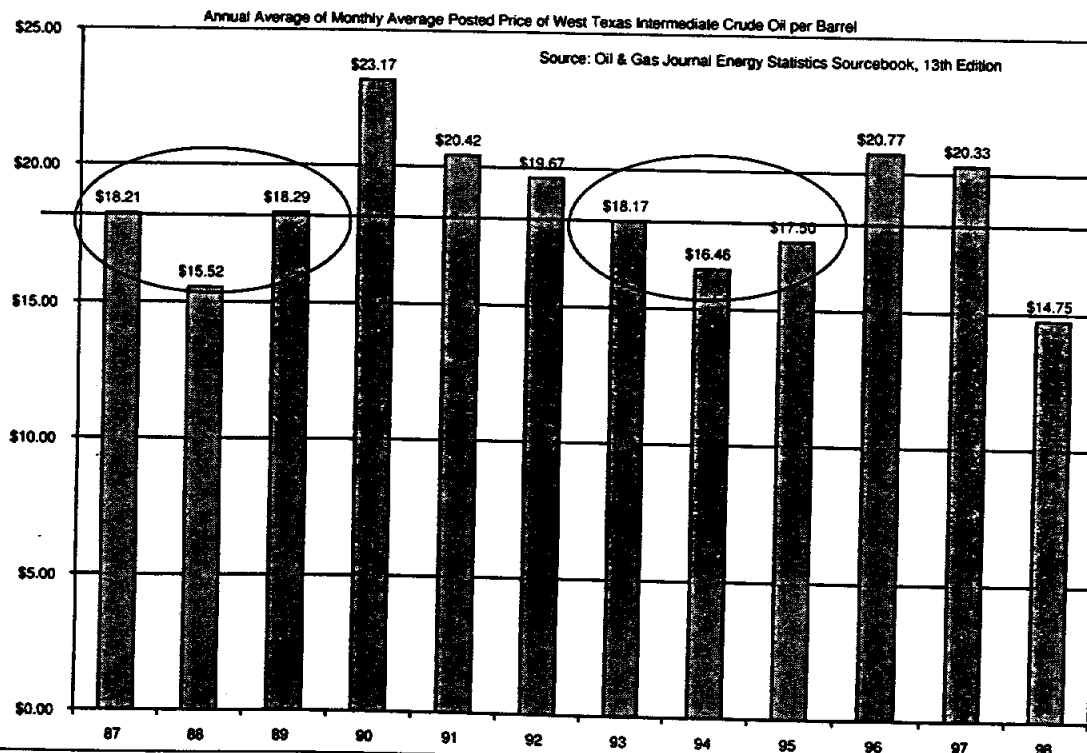
- The so-called "Asian Flu." The International Energy Agency (IEA) estimate of Asia-Pacific demand has declined from 20.6 million barrels of oil per day (mmbopd) first made in July of 1997 to 19.5 mmbopd made earlier this month.
- Warm weather in the 1997/1998 winter due to "El Niño." IEA estimates this reduced demand around 300 thousand barrels per day last winter.
- Increased Iraqi production in 1998 of about 1 mmbopd.
- OPEC's decision to increase quotas at its November 1997 meeting.

**Summary:** Total 2.25 mmbopd swing in demand and supply leading to a global stock build which in the second quarter of 1998 we estimate was 3.4 mmbopd. This compares to an average for the 1995-1997 second quarters of 1.23 mmbopd.

Pledged production cuts by OPEC of 2.6 mmbopd, to some extent, have helped rebalance supply and demand but concern about OPEC's cohesion and resolve continue to impact oil prices. Also, major oil companies' recent pessimistic public pronouncements concerning the prospects for rebounding oil prices over the next couple of years backed up by mergers and staff reductions also temper one's optimism. However, we would make the case that the current price weakness in crude oil is a temporary aberration. As the graph that follows indicates, oil prices have been on a wild ride for the last 30 years impacted by a number of propulsive events.



Can we make any sense out of this pattern in order to divine what prices will do? The graph that follows shows just the last 12 years. Despite the volatility this graph portrays, if we draw a visual average through the bars on the graph, around \$18.21 per barrel emerges. The actual mathematical average is \$18.60 per barrel.





The two ovals on the slide indicate what we might call a "rebound" pattern. The question is whether we will see a repeat of this pattern in the 97-99 period or the kind of multi-year slide we saw in the periods 1979 through 1986 or 1990 to 1994.

We would argue that we are more likely to see a "rebound" than a "slide." Both slides in the last 30 years have been caused by artificial factors—the oil shocks of the 1970s and the Gulf War effect in 1990/91. These events created dramatic price increases that were followed by multi-year declines.

On the other hand, rebounds typically take 1 year. The dips are preceded by mild weather or some other minor event like OPEC quota wrangling (1988) or the Metallgesellschaft oil trading disaster (1994) and take about a year to turn around.

We believe that the current oil price situation is a cross between a "slide" and a "rebound." It was caused by essentially "natural" or market forces rather than geopolitical ones like most rebounds. On the other hand, runaway growth in Asia-Pacific fueled by cronyism and corruption was a man-made phenomenon which more characterize "slides."

Our forecast is WTI prices in the \$14-\$16 range between now and year-end 2000 with a return to the \$18 mean in 2001 and beyond.

## APPENDIX II: CRUDE OIL PRODUCTS BREAKDOWN

### A BARREL OF CRUDE OIL

Most Americans know that motor gasoline is refined from crude oil. Yet many are unaware that a barrel of crude oil contains 42 gallons, and that gasoline is only one of a number of products refined from it. In 1985, one barrel of crude oil typically yielded the following products:

Product	Gallons	Percentage of Barrel
Finished Motor Gasoline	19.15	45.6
Finished Aviation Gasoline	0.08	0.2
Liquefied Gases & Ethane	1.30	3.1
Naphtha – Type Jet Fuel	0.71	1.7
Kerosene – Type Jet Fuel	3.32	7.9
Kerosene	0.34	0.8
Distillate Fuel Oil	9.07	21.6
Residual Fuel Oil	2.98	7.1
Petrochemical Feedstocks	1.18	2.8
Special Naphthas	0.17	0.4
Lubricants	0.50	1.2
Wax	0.04	0.1
Petroleum Coke	1.55	3.7
Asphalt & Road Oil	1.34	3.2
Still Gas <sup>1</sup>	1.97	4.7
<u>Miscellaneous</u>	<u>0.21</u>	<u>0.5</u>
Yield	43.89	104.5
<u>Processing Gain</u> <sup>2</sup>	<u>-1.89</u>	<u>-4.5</u>
Total Crude Oil	42.00	100.0

Not all commodities come in 42-gallon barrels. For example Whiskey, flour, and apples are each transported in barrels of different sizes. The sizes of the barrel types were determined by the barrel makers, or coopers, who originally constructed them. When oil was first brought to the market in commercial quantities, it was shipped in whatever barrels were available. Price was set by the barrel, no matter what volume of oil the barrel contained. In 1866, the container for oil was universally standardized as the herring barrel, containing 42 gallons. Legend has it that this number originated in the 15th century, when King Edward IV of Norway decreed the standard volume of a herring barrel to be 42 gallons.

<sup>1</sup> Any form or mixture of gas produced in refineries by distillation, cracking, reforming and other processes. The principal constituents are methane, ethane, propane, propylene, butanes, butylene, etc. Excludes still gas used as a petrochemical feedstock.

<sup>2</sup> The volumetric amount by which total output is greater than input. This difference is due to the processing of crude oil into products, which, in total, have a lower specific gravity than the crude oil processed. Therefore, in terms of volume (barrels), the total output of products is greater than the input.

Statistics from this information sheet were taken from Petroleum Supply Annual 1985.

**Howard Weil Comment:** It should be noted that many of the above products like gasoline and naphtha require additional processing and additives in order to make usable end products, they are not produced directly from the process of separating out the various carbon chains that constitute crude oil. Additionally, the above mix assumes a certain average gravity of a barrel of oil. Heavier gravity oil will produce a "heavier" slate of products—more residual, coke, and asphalt for instance.

Publicly mentioned companies in this report:

Company	Ticker	Price
Amoco Corporation	AN	\$57.25
Atlantic Richfield Company	ARC	\$64.13
British Petroleum Company PLC	BP	\$89.00
Chevron Corporation	CHV	\$83.00
Conoco Inc.	COC	\$20.50
Daimler Chrysler	DCX	\$91.31
Elf Aquitaine	ELF	\$54.19
ENI SPA	E	\$63.00
Enron Corp.	ENE	\$56.13
Exxon Corporation	XON	\$75.94
Halliburton Company Holding Co.	HAL	\$31.81
Kerr McGee Corporation	KMG	\$37.00
Lyondell Petrochemical	LYON	\$27.13
McDermott International Inc.	MDR	\$24.94
Mobil Corporation	MOB	\$90.63
Phillips Petroleum Company	P	\$41.88
Praxair Inc.	PX	\$33.50
Raytheon Company	RTN'A	\$51.69
Repsol SA	REP	\$54.25
Rentech, Inc.	RNTK	\$0.75
Royal Dutch Petroleum Company	RD	\$48.00
Syntroleum Corporation	SYNM	\$6.31
Texaco Inc.	TX	\$52.63
Tosco Corporation	TOS	\$22.69
Total	TOT	\$49.38
Unocal Corporation	UCL	\$30.56
USX Marathon Group Inc.	MRO	\$27.88
Williams Companies Inc.	WMB	\$30.13
YPF Sociedad Anonima	YPF	\$27.06

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